

Adhesion Control Method Based on Fuzzy Logic Control for Four-Wheel Driven Electric Vehicle

2010-01-0109

Published
04/12/2010

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ABSTRACT

The adhesion control is the basic technology of active safety for the four-wheel driven EV. In this paper, a novel adhesion control method based on fuzzy logic control is proposed. The control system can maximize the adhesion force without road condition information and vehicle speed signal. Also, the regulation torque to prevent wheel slip is smooth and the vehicle driving comfort is greatly improved. For implementation, only the rotating speed of the driving wheel and the motor driving torque signals are needed, while the derived information of the wheel acceleration and the skid status are used. The simulation and road test results have shown that the adhesion control method is effective for preventing slip and lock on the slippery road condition.

INTRODUCTION

Electric vehicle (EV) is a promising solution for environment and energy problem, and using in-wheel-motor drive has also merit in realizing high performance control with low cost, quick and precise torque generation, and easy controller design [1, 2, 4]. Many new control techniques (e.g., traction control, anti-lock braking control, direct yaw moment control and integrated chassis control, etc.) are being studied for electric vehicle driven by in-wheel-motor independently. The new control techniques will give a great possibility for improving the vehicle stability, safety and comfort.

The adhesion control can improve a driver's ability to maneuver a vehicle under adverse conditions, such as on a wet or icy road. It provides for fast and stable acceleration and braking by maximizing the adhesion force between the vehicle's tires and the road. The anti-slip control also improves steer-ability by preventing the wheels from slipping during cornering maneuvers. Since effective control of a vehicle's motion is essential for lateral and longitudinal guidance systems, adhesion control becomes an important part of the active safety technology.

Many adhesion control techniques are based on slip ratio control [1, 3]. For optimizing the adhesion force, the accurate vehicle speed and road condition information are needed. On the contrary, some new control technologies[1, 13, 5,6,7,8,9,10, 14] are proposed, which do not need the road condition information and vehicle speed, but some of the regulation motor torque command is big and oscillatory. The torque oscillation will lead to acoustic noise and degrade the driving comfort.

This paper proposed a novel adhesion control method based on fuzzy logic control, which can maximize the adhesion force without road condition information and vehicle speed signal, and has no acoustic noise. It only needs the rotating speed of the driving wheel and the motor torque, while the derived information of the wheel acceleration and the observation of the skid state are used. The performance and

feasibility are studied by software simulation and experiment on an in-wheel-motor drive electric vehicle.

DYNAMIC MODEL

ONE-WHEEL VEHICLE DYNAMIC

To cope with slip phenomena, a simplified one-wheel vehicle model without considering the rolling, pitching and air resistance is used, which is shown in Fig.1.

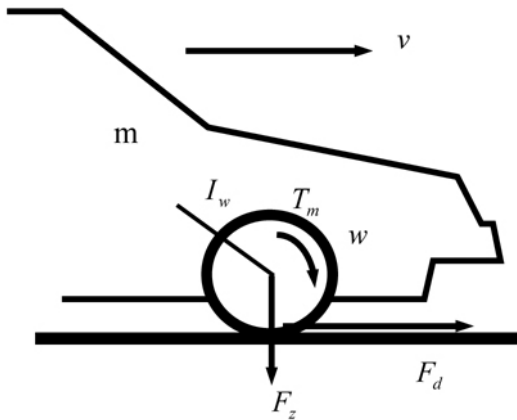


Fig.1. One-wheel vehicle model

The motion equations of wheel and chassis can be obtained as

$$I_w \frac{d\omega}{dt} = T_m - F_d r \quad (1)$$

$$m \frac{dv}{dt} = F_d \quad (2)$$

Where, T_m is motor torque (N-m), F_d is traction force (Newtons), r is wheel radius(meters), I_w is wheel inertia (kgm^2), m is one fourth of vehicle mass (kg), ω is wheel rotating speed (rad/s) and v is vehicle velocity (m/s). F_d is the driving/braking force between the wheel and the road. It has nonlinear relationship with the slip ratio λ , and is defined as

$$F_d = F_z \mu(\lambda) \quad (3)$$

where F_z is the axial weight, μ is the adhesion coefficient. The value of μ is highly dependent on tire characteristics (compound, wear, aging, etc.) and road surface conditions (dry, icy, gravel, tarmac, etc.), but it can be primarily regarded as function of the slip ratio λ between the two contacting surfaces. The λ is defined as

$$\lambda = \frac{\omega r - v}{\max(\omega r, v)} \quad (4)$$

TIRE MODEL

In recent years, the stationary inflated tire model research is becoming more perfect, and various tire models in different driving condition are established. In this paper, a “Magic Formula” tire model [11, 12] made by H.B. Pacejka is chosen. The general mathematical representation is given as

$$Y = D \sin \{ C \arctan [B X (1 - E) + E \arctan (B X)] \} \quad (5)$$

where Y is output variable (longitudinal force F_x (F_d), lateral force F_y , or self aligning torque M_z), X is longitudinal slip ratio (λ) or side slip angle, B is stiffness factor, C is shape factor (defining the output shape as F_x , F_y or M_z), D is peak value with respect to the X axis, BCD is cornering stiffness (slope at the origin) and E is curvature factor (defining the shape near the maximum output).

The $\mu - \lambda$ curve is shown as Fig.2. It can be seen that for various road conditions, the peak of adhesion force and its corresponding slip ratio are significantly different. In order to work in the stable region (slant line area), the slip ratio should be controlled in the range of 5% to 25% for different road conditions.

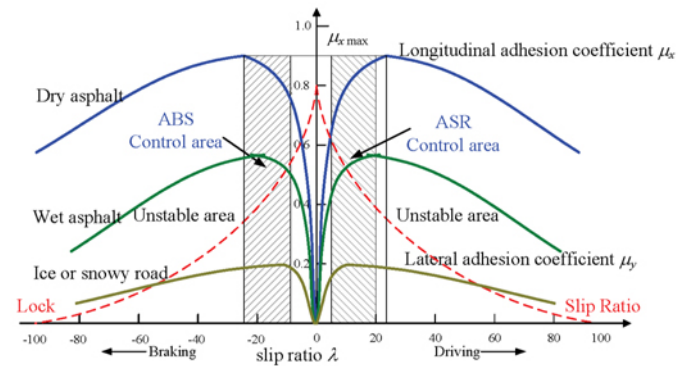


Fig.2. $\mu - \lambda$ characteristics

ADHESION CONTROL SYSTEM DESIGN

In this section, a new adhesion control is proposed based on fuzzy control. As well known, when accelerating or braking on a wet or snowy road, slip ratio will increase. If slip ratio increases to the unstable area, the road adhesion force will decrease greatly, the wheel slip or wheel lock will occur and longitudinal performance will be degraded. If the wheel is slipped or locked, the lateral adhesion force becomes

drastically smaller, and this will causes serious problems like drift-out or spin while corning or disturbing by lateral force.

There are several methods to prevent slip without directly control the slip ratio. One way is to control the $d\mu/d\lambda$ not smaller than zero [13], to keep the tire operation point to be remained in the positive slop region of the μ - λ characteristics curve showed in Fig.2. Although the adhesion control performance is good, the vehicle speed signal is needed, and it is not easy to apply to the four-wheel driven vehicle. The second way is to control the motor output torque according to the values of dF_d/dF_m [5], where F_m is the force equivalent to motor torque (Newtons). But the paper gives out the fixed values of dF_d/dF_m for the detection of slip and re-adhesion status, the values are not suitable for different driving conditions and different vehicle parameters. The third way is to detect the slip status by dF_d/dF_m and $d(dF_d/dF_m)/dt$ [14], and to regulate the motor torque by fuzzy control logic. But the regulation motor torque command is largely oscillatory and the driving comfort is degraded.

The reason of oscillatory in [14] is mainly for that the wheel acceleration is not controlled. When the wheel slip is occurred, the motor torque has to regulate greatly to make the wheel to be re-adhesive. If the wheel acceleration can be controlled in a proper range, the wheel can be controlled to move to the slip status slowly, that means the slip ratio will be changed slowly, so that only a smaller regulation motor torque could make the wheel to be re-adhesive.

In this paper, a proper limit value of wheel acceleration and a simple slip status detection method are analyzed and designed. The proposed adhesion control method is based on a fuzzy logic with the inputs of the wheel acceleration limit and the slip status detection.

LIMIT VALUE OF WHEEL ACCELERATION

The wheel acceleration α is related to the motor torque T_m and slip ratio λ . The relationship among the three variables and the wheel acceleration α can be derived from Eq. (4), (1) and (2).

$$\frac{d\lambda}{dt} = \frac{-\frac{dv}{dt} \cdot \omega r + \frac{d\omega}{dt} \cdot v r}{\omega^2 r^2} = \frac{[I_w + (1 - \lambda)mr^2] \cdot \alpha - T_m}{\omega mr^2} \quad (6)$$

$$\alpha = \frac{d\omega}{dt} = \frac{T_m}{I_w + mr^2(1 - \lambda)} + \frac{\omega mr^2}{I_w + mr^2(1 - \lambda)} \frac{d\lambda}{dt} \quad (7)$$

If the slip ratio λ is changed slowly, it means $d\lambda/dt \approx 0$. So that,

$$\alpha \approx \frac{T_m}{I_w + (1 - \lambda)mr^2} \quad (8)$$

The best adhesion control result is that the slip ratio is increased gradually and is maintained at the optimal slip ratio λ_p near the peak adhesion coefficient μ_{max} . At this time, the wheel acceleration α_p can be defined as Eq. (9). If the wheel acceleration α can be controlled smaller than that of α_p , the wheel slip will not occur.

$$\alpha_p = \frac{T_m}{I_w + (1 - \lambda_p)mr^2} \quad (9)$$

Fig.3 shows the simulation curve of λ and α when the vehicle is accelerated on a slippery road with initial speed of 5km/h. The simulation model consists of Eq. (1),(2),(3),(4),(5). The simulation parameters of $m=200\text{kg}$, $T_m=110\text{N}\cdot\text{m}$, $\mu_{max}=0.2$ and $\lambda_p=0.066$ are used. The slip ratio curve and acceleration curve b show the wheel status. When λ curve go through the point $\lambda_p=0.066$ at about 0.83s, the acceleration of curve b also grows big suddenly, it indicates that the wheel begins to slip. The curve a and curve c are the acceleration curve calculated by Eq. (9) with $\lambda_p=0.25$ and 0.066 respectively. The curve d is the acceleration curve calculated by Eq. (8).

<figure 3 here>

The wheel acceleration curve b is below the curve a before the wheel slips. So that the curve a can be used as the limit value of acceleration. Here the λ_p for curve a can be tuned to a relatively big value of 0.25 which would be suitable for any road condition. It should be pointed out that the limit value of acceleration is a curve calculated according to the motor torque T_m and it is not a fixed value as convention.

SLIP STATUS DETECTION

From Fig.2, it can be seen that the slip status changes at the μ_{max} point. The time derivative of Eq. (3) is as following. The axial weight changing is ignored.

$$\frac{d\mu}{dt} = \frac{1}{F_z} \frac{dF_d}{dt} = \frac{1}{F_z} \frac{dF_d}{dT_m} \frac{dT_m}{dt} \quad (10)$$

According to Eq. (10), the relationship among $d\mu/dt$, dF_d/dt , dT_m/dt and the wheel slip status can be analyzed. The wheel status can be detected as 1) When $dF_d/dT_m < 0$, wheel is in slip status; 2) When $dF_d/dT_m > 0$, wheel is in stable status or