A Road Identification Method Based on Road Slope Information for Four-Wheel Independent Drive Electric Vehicles

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Abstract. Four-wheel independent drive electric vehicles (4WID EV) drive safely and stably, which depends on current road conditions, especially road friction coefficient and slope, and different driving control strategies are used according to road conditions. Therefore, a road identification method is proposed to estimate the road information. Firstly, we design a road identification algorithm to identify the current road conditions of 4WID EV, and calculate the optimal slip ratio of the current road surface by curve fitting method. When the wheel slip ratio is controlled near the optimal slip ratio, the wheel adhesion coefficient can be maximized to prevent the wheel from slipping. Then, a slope identification algorithm based on Luenberger state observer is designed to identify the various slopes of uphill and downhill, and it provides a reference for the calculation of the slope compensation torque. Finally, through the joint simulation platform of MATLAB/Simulink and Carsim, it shows that the proposed road identification can identify the current road conditions and slope effectively.

1. Introduction

Four-wheel independent drive electric vehicles (4WID EV) don’t have transmission part, that greatly improves the transmission efficiency and maneuverability [1-6]. In order to prevent the vehicle from slipping on the low adhesion road and uncontrollable speed on the slope road, various control strategies are designed, and the important condition for these strategies is to identify the road [7].

Although the sensor direct detection can more accurately identify the road surface state, the working environment of such sensors requires high standards and costly, so cannot be widely used [8-9]. In reference [10], an adaptive Kalman filtering is used to estimate the traction forces of the driving wheels and vehicle information, and then road identification is carried out. But when the wheels run at high speed, the identification accuracy would be low. Reference [11] estimates the wheel slip ratio and road adhesion coefficient through the known vehicle information, compares with the standard curve. This method has high accuracy when the standard curve is known. In the research of slope identification, parameter estimation has become an important method to obtain the slope of road [12-14]. In reference [15], dynamics methods are used to identify the road slope. This method does not depend on system model, but the calculation is complex and the real-time performance is bad. In reference [16], the global positioning system (GPS) is used to estimate the slope, but the low frequency of GPS will cause large estimation error. In reference [17], Kalman filtering is used to estimate the slope of road in real time, but when the slope changes greatly, the identification accuracy decreases obviously.
This paper proposes the road identification method, and the simulation results show that this method can effectively identify the road friction coefficient and slope. The structure of this paper is as follows: Chapter 2, we establish and analyze the dynamic model of single wheel and the dynamic model of 4WID EV on slope. Chapter 3 is about a road identification algorithm to identify, and calculate the optimal slip ratio of the current road by curve fitting method. Chapter 4, we analyze and derive the state space expression of the system, and design the slope identification algorithm based on Luenberger state observer. Chapter 5, the road identification method is validated by the joint simulation platform of MATLAB/Simulink and Carsim.

2. Model building of 4WID EV

2.1. Single wheel dynamics model
Four wheels of four-wheel independent drive electric vehicle have the same dynamic characteristics and are independent of each other. Therefore, we select one of the wheels and establish the dynamic model as shown in Figure 1. Denote \( i, j \in \{fl, fr, rl, rr\} \), where \( fl, fr, rl, rr \) are left front wheel, right front wheel, left rear wheel and right rear wheel respectively.

![Wheel dynamics model](image)

**Figure 1.** Wheel dynamics model

The equation of wheel motion can be expressed by formula (1).

\[ \dot{\omega}_i = J \omega_i = T_i - F_{x-i} \cdot r \tag{1} \]

Where, \( J \) is the equivalent mass moment of inertia, \( \omega_i \) is the rotational speed of the wheel, \( T_i \) is the driving torque of the wheel, \( F_{x-i} \) is the longitudinal force of the wheel, and \( r \) is the wheel radius.

2.2. Dynamic model of vehicle on slope
In this paper, 4WID EV is the object of force analysis, and the following assumptions are made. (1) Ignoring the lateral and yaw motion of the vehicle; (2) The motion characteristics of the four wheels are the same; (3) The slope of the road do not exceed 20%; (4) Ignoring the air resistance of the vehicle; (5) The vehicle mass is uniformly-distributed.

The force analysis of 4WID EV on slope is shown as follows.

![Force analysis](image)

**Figure 2.** The force analysis of 4WID EV on slope
Figure 2 is force analysis of a 4WID EV on the $\theta$ degree slope. The 4WID EV is subjected to four wheel driving forces $F_d$, ramp resistance $F_r$, rolling resistance $F_f$, and braking force $F_b$. According to Newton’s second law, the motion equation is shown in formula (2).

$$m\ddot{v} = F_d - F_f - F_r - F_b$$

$$= F_i - F_f - F_r - F_b$$

$$= \frac{Ti_i}{r} - mg f \cos \theta - \beta_b T_{\text{max}} - mg \sin \theta$$

Where, $\ddot{v}$ is the longitudinal acceleration of the vehicle, $F_i$, $F_f$, $F_r$, and $F_b$ are the longitudinal force on the left front, right front, left rear and right rear tires respectively, $T_i$ is the driving force of four wheels, $F_i$ is the driving force of four wheels, $F_f$ is the rolling resistance, $F_r$ is the braking force, $F_i$ is the slope resistance, $T$ is the sum of the output torque of the four wheel motors, $l_i$ is the transmission ratio, $i_o$ is the main reducer ratio, $\eta_i$ is the mechanical transmission efficiency, $r$ the radius of the wheel, $m$ is the whole vehicle mass, $g$ is the acceleration of gravity, $\theta$ is the degree of the road slope, $f$ is the rolling resistance coefficient. $\beta_b$ is the opening of brake pedal, $T_{\text{max}}$ is the maximum brake torque.

3. Road surface identification

The optimal slip ratio of wheels varies with different road surface, so it is necessary to get the current road information by road identification, and then estimate the optimal slip ratio of wheels. Wheel slip rate can be obtained by formula (3).

$$s_i = \frac{\omega_i r - \ddot{v}}{\omega_i r}$$

Where, $s_i$ is the slip ratio of the wheel, $\omega_i$ is the rotational speed of the wheel.

The adhesion coefficient of wheels, which can be calculated by formula (4).

$$u_i = \frac{F_{x_i}}{F_{z_i}}$$

Where, $u_i$ is the adhesion coefficient, $F_{x_i}$ is the longitudinal force of the wheel and $F_{z_i}$ is the vertical force of the wheel.

According to formula (1), the wheel longitudinal force can be obtained as formula (5).

$$F_{x_i} = \frac{T_i}{r} - \omega_i$$

The vertical force of wheels can be obtained by formula (6).

$$F_{x_i} = \frac{1}{2} mg \frac{l_f}{l_f + l_r}$$

Where, $g$ is the acceleration of gravity; $l_f$ is the distance from the center mass of the vehicle to the front axle and $l_r$ is the distance from the center mass to the rear axle.

The $u-s$ curve of standard road is proposed by Burckdart [18], as shown in formula (7).

$$u(s) = C_1 (1 - e^{-C_2 s}) - C_3 s$$

Where, $C_1$, $C_2$, $C_3$ are the coefficient related to the road.

According formula (7), we get.
\[
\begin{aligned}
    s_{\text{opt}} &= \frac{1}{C_2} \ln \frac{C_3}{C_1} \\
    u_{\text{max}} &= C_1 \frac{C_3}{C_2} (1 + \ln \frac{C_3}{C_1})
\end{aligned}
\]  

(8)

Where, \( s_{\text{opt}} \) is the optimum slip ratio and \( u_{\text{max}} \) is the maximum road adhesion coefficient.

Dry asphalt, dry cement, wet asphalt, wet pebble, snow and ice are selected as standard road. Relevant parameters are shown in Table 1.

| Road surface      | \( C_1 \) | \( C_2 \) | \( C_3 \) | \( s_{\text{opt}} \) | \( u_{\text{max}} \) |
|-------------------|----------|----------|----------|----------------|----------------|
| ice               | 0.05     | 306.39   | 0.001    | 0.03           | 0.05           |
| snow              | 0.1946   | 94.129   | 0.0646   | 0.06           | 0.1907         |
| wet pebble        | 0.4004   | 33.7080  | 0.1204   | 0.14           | 0.34           |
| wet asphalt       | 0.8570   | 33.822   | 0.3470   | 0.13           | 0.8013         |
| dry cement        | 1.1973   | 25.168   | 0.5373   | 0.16           | 1.09           |
| dry asphalt       | 1.2801   | 23.99    | 0.52     | 0.17           | 1.17           |

The \( u-s \) curve of standard road is shown in Figure 3.

![Figure 3 u-s curve of standard road](image)

In reference [19], the weight coefficients of each standard road surface are determined according to the utilization adhesion coefficient of wheels and the adhesion coefficient of standard road surface, as shown in formula (9).

\[
x_k = \frac{1}{u_k(s_k) - u_k} + \varepsilon \quad (k = 1, 2, L, 6)
\]  

(9)

Where, \( k = 1, 2, \ldots, 6 \) are ice, snow, wet pebbles, wet asphalt, dry cement and dry asphalt road, \( x_k \) is the weight coefficient, \( u_k(s_k) \) is the adhesion coefficient, \( \varepsilon \) is a positive number close to zero.

According to the weight coefficients of each road surface, the peak adhesion coefficient of the current road and the optimal slip rate of the wheel can be calculated.
where, $\mu_{\text{max}} (k = 1, 2, 3, 6)$ and $s_{\text{opt}} (k = 1, 2, 3, 6)$ are the peak adhesion coefficients of ice, snow, wet pebble, wet asphalt, dry cement and dry asphalt road and the optimal slip rate of wheel, which can be obtained by looking up Table 1.

4. Slope identification based on luenberger state observation

We propose a road slope identification based on Luenberger state observer. Since the vehicle runs on a slope less than 20%, $\sin \theta \approx \cos \theta \approx 1$. Formula (6) can be linearized into Formula (10).

$$
\dot{v} = \frac{T_i \eta}{r} - mgf - \frac{\beta g T_{\text{max}}}{r} - mg\theta
$$

Denote $L_{\text{max}} = \max_{1, 2, 3, 6}\mu_k$ and $L_{\text{opt}} = \max_{1, 2, 3, 6}s_k$ are the peak adhesion coefficients of ice, snow, wet pebble, wet asphalt, dry cement and dry asphalt road and the optimal slip rate of wheel, which can be obtained by looking up Table 1.

The speed $v$ and slope $\theta$ are state variables, so the state space expression of system is as follows.

$$
\begin{align*}
\dot{x} &= Ax + Bu \\
y &= Cx
\end{align*}
$$

Where, $x = \begin{pmatrix} v \\ \theta \end{pmatrix}, \dot{x} = \begin{pmatrix} \dot{v} \\ \dot{\theta} \end{pmatrix}, y = v, u = F_x, A = \begin{bmatrix} 0 & -g \\ 1/m & 0 \end{bmatrix}, B = \frac{1}{m}, C = [1 \ 0].$

The Luenberger state observer requires the observability of the system, that is, the matrix $W$ must be full rank matrix, and the rank of $W$ is as follows (14).

$$
\text{rank} W = \text{rank} \begin{bmatrix} C \\ CA \end{bmatrix} = \text{rank} \begin{bmatrix} 1 & 0 \\ 0 & g \end{bmatrix} = 2
$$

$W$ is full rank matrix, so the state observer can be designed by pole assignment.

The Luenberger state observer is introduced, and the state space expression is as follows.

$$
\begin{align*}
\dot{x}_e &= Ax_e + Bu - HC(x_e - x) \\
y_e &= Cx_e
\end{align*}
$$

Where, $x_e = \begin{pmatrix} v_e \\ \theta_e \end{pmatrix}$ is the observation value of the state variable $x$, $H = \begin{pmatrix} h_l \\ h_r \end{pmatrix}$ is the state observer feedback gain matrix, $y_e$ is the observation value of the output $y$.

According to formula (13) and formula (15), the error vector is obtained as follows.

$$
\dot{x} - \dot{x}_e = (A - HC)(x_e - x)
$$

Obviously, when $x_e(t) = x(t)$, there would be always $x_e(t) = x(t)$, so the output feedback does not work, when $x_e(t) \neq x(t)$, output feedback could works. If the eigenvalue of $(A - HC)$ has a negative real part, the error between the observed value $x_e$ and the actual value $x$ will decay exponentially, and the decay rate depends on the pole configuration of $(A - HC)$ [20-21].

In order to allocate the zero-pole of the system and determine the value of the matrix $H$, so it is necessary to obtain the characteristic polynomial of the Luenberger state observer, as follows.
Where, assume $m, n$ are the eigenvalue of the Luenberger state observer, then.

$$f(\lambda) = (\lambda - m)(\lambda - n)$$

$$= \lambda^2 - (m + n)\lambda + mn$$

According to formula (17) and formula (18), the values of $h_1, h_2$ are as follows.

$$h_1 = -(m + n)$$

$$h_2 = \frac{-mn}{g}$$

The eigenvalues of the Luenberger state observer should satisfy the following conditions:

1. The two eigenvalues must be negative, otherwise the system will be unstable.
2. If the eigenvalues are too close to the imaginary axis, the response of the system will slow down.
3. If the eigenvalues are too far from the imaginary axis, the system will be more sensitive to noise.

According to the above conditions, we denote $m = -2$ and $n = -3$, then $h_1 = 5, h_2 = -\frac{6}{g}$. By introducing $H$ matrix into formula (15), the expression of state observation can be obtained, as follows.

$$\begin{align*}
\dot{v}_i &= -g\theta + \frac{F_x}{m} - 5(v_i - v) \\
\dot{\theta}_i &= \frac{6}{g}(v_i - v)
\end{align*}$$

According to formula (20), the Luenberger state observer can be obtained, as shown in figure 4.

![Figure 4. Slope identification based on Luenberger state observer](image)

If the estimated slope value $\theta_i$ is greater than 0, it is on the uphill slope; if $\theta_i$ is less than 0, it is on the downhill slope; if $\theta_i$ is equal to 0, it is on the flat road.

5. **Simulation**

In order to verify the performance of the proposed control algorithm, a joint simulation platform based on MATLAB/Simulink and Carsim is built.

**Table 2. Vehicle parameters**

| Parameter                          | Value |
|------------------------------------|-------|
| Vehicle mass (kg)                  | 2150  |
| Wheel effective radius (m)         | 0.3262|
| Maximum torque (N·m)               | 320*4 |
| Distance from front/rear axle to CG (m) | 1.35  |
| Front track width (m)              | 1.55  |
| Rear track width (m)               | 1.53  |
| The equivalent mass moment of inertia (kg·m²) | 0.6  |
5.1. Uphill road with different adhesion coefficients
4WID EV drives in a straight line at a constant speed 60km/h, and three road conditions are, 1) \( u = 0.2 \), slope=5\%, 2) \( u = 0.3 \), slope=10\%, 3) \( u = 0.8 \), slope=15\%.

The simulation results show that, the time of surface identification is very short, about 0.5 second, and the process of slope identification time is about 5 seconds. On the first road, identified adhesion coefficient is 0.1907, the road is closely resemble the snow road, and identified slope is 5.6\%. On the second road, identified adhesion coefficient is 0.34, the road is closely resemble the wet pebble road, and identified slope is 10.8\%. On the third road, identified adhesion coefficient is 0.8013, the road is closely resemble the wet asphalt road, and identified slope is 16\%.

5.2. Downhill road with different adhesion coefficients
4WID EV drives in a straight line at a constant speed 60km/h. Three road conditions are, 1) \( u = 0.2 \), slope=-5\%, 2) \( u = 0.3 \), slope=-10\%, 3) \( u = 0.8 \), slope=-15\%. 

![Figure 5. Identified adhesion coefficient (\( u = 0.2 \), slope=5\%)](image1)

![Figure 6. Identified adhesion coefficient (\( u = 0.3 \), slope=10\%)](image2)

![Figure 7. Identified adhesion coefficient (\( u = 0.8 \), slope=15\%)](image3)

![Figure 8. Identified slope (\( u = 0.2 \), slope=5\%)](image4)

![Figure 9. Identified slope (\( u = 0.3 \), slope=10\%)](image5)

![Figure 10. Identified slope (\( u = 0.8 \), slope=15\%)](image6)
The simulation results show that, downhill and uphill are similar. The first road is identified as the snow road, and identified slope is -4.9%. The second road is identified as the wet pebble road, and identified slope is -10.1%. The third road, the road is identified as the wet asphalt road, and identified slope is -15.2%.

From the above, the road identification method proposed in this paper can effectively identify the adhesion coefficient and slope of the current road whether it is uphill or downhill.

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