A road surface identification method for a four in-wheel-motor drive electric vehicle

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Abstract: A four in-wheel-motors drive electric vehicle needs to identify the road surface in order to optimise the slip-ratio control. This paper builds a four in-wheel-motor drive electric vehicle dynamic model and estimates the vehicle speed and driving forces of four wheels by the method of adaptive filtering. According to the calculated tyre adhesion coefficient and slip ratio, the paper employs the method of combining fuzzy inference with slope determination to evaluate the road type and determine the target slip ratio, and obtains a better slip ratio regulation effect through timely and precise adjustment of output torque of the in-wheel motors. The simulation and experiment results confirm that it is a reliable design.

Keywords: four in-wheel-motor drive; electric vehicle; road surface identification; method.

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1 Introduction

Since the road condition is complicated, when the vehicle is driving on the road, the adhesion between the tyre and road surface is quite different and may change constantly. To increase the utilisation rate of adhesion coefficient between the tyre and road surface and guarantee the driving safety of vehicle, appropriate traction anti-skid control is needed for the tyre (Pusca et al., 2002). For real-time identification of adhesive condition of road surface, selecting an optimal slip ratio control objective is the key to the traction anti-skid control of vehicle. The vehicle dynamics depend on the non-linear tyre friction to a great extent (Laura, 1995), and precise information about tyre friction and vehicle speed is important information for road surface identification.

The research group of the author has carried out research on four in-wheel-motor drive (FIWMD) and independent steering electric vehicle (EV). The vehicle is refitted from Chery QQ vehicle, the engine, drive system, steering system and suspension of original vehicle are removed, and it is designed with a new suspension and employs four in-wheel-motors for independent drive and four motors to control the steering independently, thus realising control by wire of steering and drive (Figure 1). The traditional vehicle usually obtains the speed information from the speed of non-drive wheel, and the FIWMD EV has no non-drive wheel, so its speed needs estimation. This paper builds an FIWMD EV dynamic model and estimates the vehicle speed and driving forces of four wheels by the method of adaptive filtering. According to the calculated tyre adhesion coefficient and slip ratio, the paper employs the method of combining fuzzy inference with Slope determination to evaluate the road type and determine the target slip ratio, and obtains a better slip ratio regulation effect through timely and precise adjustment of output torque of drive motor.

2 Estimation of vehicle speed and driving forces of four wheels

2.1 Dynamic model of FIWMD EV

Longitudinal movement of vehicle body and forces of tyre shall be considered in building the dynamic model, the forces acting on the EV are shown in Figure 2, and the forces acting on the driving wheel are shown in Figure 3. The dynamic model is:

\[
\dot{\text{v}} = \frac{1}{m} \left[ F_1 + F_2 + F_3 + F_4 \right]
\]

\[
J_1 \dot{\omega}_1 = T_1 - F_1 r
\]

\[
J_2 \dot{\omega}_2 = T_2 - F_2 r
\]

\[
J_3 \dot{\omega}_3 = T_3 - F_3 r
\]

\[
J_4 \dot{\omega}_4 = T_4 - F_4 r
\]

wherein \( \text{v} \) is the longitudinal velocity of vehicle; \( m \) is the mass of vehicle; \( r \) is the radius of tyre; \( F_i \) \((i = 1–4)\) are the driving forces of four tyres, respectively; \( J \) is the sum of rotary inertia of all the rotating parts connected to tyres; \( \omega_i \) \((i = 1–4)\) are the angular velocities of four wheels, respectively; \( T_i \) \((i = 1–4)\) are the driving torques applied on four wheels, respectively.

Figure 1 Four in-wheel-motor drive electric vehicle (see online version for colours)

Figure 2 Forces acting on the EV
Write the formula (1)~(5) in the form of state equation:

\[
\begin{align*}
\dot{x} &= A x + A_f F + B_u \\
z &= H x + H_f F
\end{align*}
\]

wherein \( x = [v, \omega_1, \omega_2, \omega_3, \omega_4]^T \) is the state variable; \( u = [T_1, T_2, T_3, T_4]^T \) is the input variable; \( f = [F_1, F_2, F_3, F_4]^T \) is the friction vector; \( z = [v, \omega_1, \omega_2, \omega_3, \omega_4]^T \) is the measurement vector; \( A \) is the state matrix; \( A_f \) is the friction state matrix; \( B \) is the control matrix; \( H \) is the observation matrix of state vector; \( H_f \) is the observation matrix of friction vector.

Assuming \( A_k = e^{AT} = L^{-1}[(sI-A)^{-1}] \); \( B_k = \int_0^T e^{AT}Bdr \), obtain the discretisation equation:

\[
\begin{align*}
x_k(k) &= A_k(k-1)x(k-1) + A_f(k-1)F(k-1) \\
& \quad + B_k(k-1)u(k-1) \\
z_k(k) &= H_k(k)x(k) + H_f(k)F(k)
\end{align*}
\]

### 2.2 Estimation of adaptive filtering algorithm

The tyre friction is related to many factors such as the wear condition of tyre, tyre pressure, vertical load and adhesive condition of tyre and road surface. To avoid the drop of calculation speed and poor real-time due to the use of complicated non-linear tyre model in the actual control strategy, the friction between the tyre and surface is deemed into an inertial element, and the output signal is an exponential type time-related random process, namely:

\[
\delta(t) = E[X(t)X(t+\tau)] = \sigma'^2 e^{-\sigma'^2 T_c} \tag{8}
\]

wherein \( T_c \) is the correlation time; \( \sigma' \) is the variance; \( \tau \) is the sampling time.

Include the friction vector into the state variable, and obtain the discrete state equation:

\[
\begin{align*}
x_k(k) &= A_k(k-1)A_f(k-1)x(k-1) \\
& \quad + A_f(k-1)F(k-1) \\
& \quad + B_k(k-1)u(k-1) + W(k-1)
\end{align*}
\]

\[
\text{wherein } A_k = \text{diag}([\delta(\tau) \delta(\tau) \delta(\tau) \delta(\tau)]) \text{ and take } \sigma' = 1; \ x(k) = [x, F(k)]^T \text{ is } n \text{-dimensional state vector of the system}; \ z(k) \text{ is the } n \text{-dimensional observation sequence of the system}; \Phi(k, k-1) = \begin{bmatrix} A_k(k-1) A_f(k-1) \\ 0 \ A_k(k-1) \end{bmatrix}
\]

is \( n \times n \)-dimensional state transfer matrix of the system; \( H(k) = [H_k(k) H_f(k)] \) is \( m \times n \)-dimensional observation matrix; \( G(k) = [B_k(k) 0]^T \) is the input matrix of the system; \( W(k) \) and \( V(k) \) are the mutually independent time-varying mean and normal white noise sequence of covariance matrix, respectively.

The state variable is estimated in the Sage-Husa adaptive filtering algorithm added with forgetting factor (see Zhou et al., 2007). In the filtering calculation, on the one hand, the predicted value is corrected constantly by means of observation, and on the other hand, the unknown or uncertain system model parameters and noise statistic parameters are estimated and corrected. Therefore, information about real-time vehicle speed and tyre driving forces is obtained.

### 3 Identification method for adhesive condition of road surface

#### 3.1 Calculation of adhesion coefficient and slip ratio

During the driving, owing to the inertia force resulting from longitudinal acceleration of vehicle, the vertical load of antero posterior axis changes, and it can be calculated in accordance with the following torque equilibrium equation in Figure 2. To highlight the research emphasis and simplify the calculation, this paper assumes that the load of single wheel is half the load of the axle.

\[
N_i L = m g b - m h_i \dot{v} \tag{11}
\]

\[
N_i L = m a + m h_i \dot{v} \tag{12}
\]

Obtain the vertical load of front drive axle is:

\[
N_i = \left( g b - v h_i \right) m / L \tag{13}
\]

The vertical load of rear drive axle is:

\[
N_i = \left( g a + v h_i \right) m / L \tag{14}
\]

wherein \( g \) is the gravity acceleration; \( a \) is the distance from the mass centre to front axle; \( b \) is the distance from the mass centre to rear axle; \( L \) is the spread of axles.

The adhesion coefficient and slip ratio of four wheels can be calculated respectively in accordance with the obtained driving forces of four wheels and vehicle speed.

\[
\mu_i = \frac{F_i}{N_i} \quad (i = 1 \sim 4) \tag{15}
\]
\[
\lambda_i = \frac{r_0_i - v}{r_0_i} \quad (i = 1\sim 4)
\]
wherein \(N_i\) is the vertical load of four wheels; \(\lambda_i\) is the corresponding slip ratio of four wheels; \(\mu_i\) is the corresponding adhesion coefficient of four wheels.

### 3.2 Identification of adhesive condition of road surface

According to the obtained wheel adhesion coefficient \(\mu\) and slip ratio \(\lambda_i\), identify the road surface type \(r_i\), through the road condition estimator (Figure 4) and in combination with the vehicle speed, determine the target slip ratio \(\lambda^*\). The road surface can be identified with the road condition estimator in the methods of combining fuzzy inference with slope determination. The road surface can be divided into four typical road surfaces (Figure 5), namely, high, medium, low and very-low adhesion road surfaces, which are represented with H, M, L and VL, respectively. Many experiments show (e.g., Gustafsson, 1998) that, when the slip ratio is low \((\lambda < 0.05)\), \(\mu\) and \(\lambda\) are approximately linear. Moreover, the simulation shows that, when fuzzy inference method is employed and the slip ratio is low, the error will be big. Therefore, when the slip ratio is small \((\lambda \leq 0.015)\) (see Figure 5), this paper judges the type of road surface by judging the value of rate of slope of \(\mu\) to \(\lambda\), \(k = \mu/\lambda\). In normal driving, the slip ratio of wheel is very small, and when the vehicle is driving on the low or very-low adhesion road surface and the road condition estimator identifies the road surface, the vehicle can remind the driver to drive carefully.

The optimal slip ratio of four typical road surfaces can be determined according to the vehicle speed and other conditions, and the fundamental principle is: in the starting acceleration and low-speed process, take the value of corresponding slip ratio of maximum adhesion coefficient; in the high and medium-speed driving process, considering the requirement of lateral adhesion coefficient, take the value which is slightly lower than the corresponding slip ratio of maximum adhesion coefficient.

### 3.3 Fuzzy inference method of road surface

As the input of fuzzy rule, \(\mu\) and \(\lambda\) are represented with VS, MS, S, M, B, MB and VB for its very small, medium small, small, medium, big, medium big and very big values, and represented with VS, S, M, B and VB for its very small, small, medium, big and very big values. Since the research EV adopts traction control system, the slip ratio is basically controlled below 0.25, and Figure 6 shows the degree of membership of \(\mu\) and \(\lambda\). With the road type \(r_i\) as the output, H, M, L and VL are used to represent the high, medium, low and very low road type, and are assigned the value of 0.8, 0.6, 0.4 and 0.2, respectively. Figure 7 shows the degree of membership of \(r_i\), and Table 1 are the fuzzy inference rules.
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Figure 7  Degree of membership of $r_t$

![Degree of membership of r_t](image)

Table 1  Fuzzy inference rules

<table>
<thead>
<tr>
<th>$r_t$</th>
<th>VS</th>
<th>S</th>
<th>M</th>
<th>B</th>
<th>VB</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\mu$</td>
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<td>VL</td>
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<tr>
<td>MS</td>
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<td>M</td>
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<td>VB</td>
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</tbody>
</table>

Assuming that, at certain speed, the optimal slip ratio of high, medium, low and very low adhesion road is 0.12, 0.15, 0.20, and 0.1, respectively, the fuzzy inference input $\mu = 0.65$ and $\lambda = 0.07$ and the output is $r_t = 0.74$, the road surface is between the high and medium adhesion road surface, and the target slip ratio is:

$$\lambda^* = 0.15 \times \frac{0.8 - 0.74}{0.8 - 0.6} + 0.12 \times \frac{0.74 - 0.6}{0.8 - 0.6} = 0.13$$

3.4 Method of slope determination

When $\lambda \leq 0.015$, the road surface condition identifier shall identify the result in the method of slope determination, and the range of slope value of four typical road surfaces shall be obtained through the experiment; Figure 5 shows the curve obtained from double-exponential-based longitudinal adhesion coefficient computation module (Bian and Li, 2005), which is used in simulation of road surface identification, and the range of slope rate of different road surfaces are:

$$\begin{cases} 
    k \leq 4 & H \\
    4 < k \leq 6 & M \\
    6 < k \leq 17 & L \\
    k > 17 & VL
\end{cases}$$

4 Simulation and experiment of road surface identification

The simulation is conducted in MATLAB/Simulink environment, and the drive motors of front and rear wheels drives the vehicle in accordance with the torque $T = 115$ N.m, the vehicle first drives on the H road surface, two seconds later on the M road surface, four seconds later on the L road surface, and six seconds later on the VL road surface. Figure 8 shows the change of related parameters of vehicle on the different road surfaces, and from the simulation result of road surface identification of Figure 9, it can be seen that the road condition estimator can identify the road surface condition in real time.

Figure 8  Change of related parameters of vehicle

![Change of related parameters of vehicle](image)

Figure 9  Identification result of road condition

The EV model can be further simplified into single wheel model. Experiments are done on the single wheel test bench developed by our group (Figure 10). The wheel with hub motor installed on the frame, the hub motor is controlled by the controller to drive the wheel, the wheel drive the double-drum to rotate, the double-drum is connected with
the flywheel which has large rotational inertia, at the same time is connected with the load motor. When the output power of the load motor is changed, the slip ratio between the wheel and the double-drum will change. The vertical load acting on the wheel can be adjusted. The surface of the double-drum has been processed into two kinds of roughness, Figure 11 is the $\mu - \lambda$ curve of the double-drum surface. The identification method for adhesive condition of road surface present above is applied to the bench. When the roughness of the double-drum is changed, according to the measured and calculated $\mu, \lambda$, the controller can identify the road condition between the wheel and the double-drum.

5 Conclusions

The dynamic model of an FIWMD EV is build, and the vehicle speed and driving forces of four wheels are estimated by the method of adaptive filtering. According to the calculated tyre adhesion coefficient and slip ratio, presents a method of combining fuzzy inference with Slope determination to evaluate the road type and determine the target slip ratio, and obtains a better slip ratio regulation effect through timely and precise adjustment of output torque of the in-wheel motors. The simulation and experiment results confirm that it is a reliable design.

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