A research on Anti-slip regulation for 4WD electric vehicle with In-wheel motors

Li Zhou, Lu Xiong[*], Zhuoping Yu

Abstract—**This paper proposes a wheel slip control strategy for 4WD Electrical Vehicle with In-wheel Motors. In the first part of this paper, a brief introduction of sliding mode control for acceleration slip regulation is given. Consider that its control effect varies with road conditions, another algorithm which can automatically adapt to different roads is designed. This method takes advantage of the peculiarity of the longitudinal static tire force curve and regulates wheel slip ratio to the detected optimal value, aiming to maximize the traction force while preserving sufficient lateral tire force. Simulation results show that the slip rate can be regulated to a value around the optimal slip ratio, and the driving torque is very close to the maximum transmissible torque. The control strategy achieves stronger stability, shorter driving distance and hence better control performance.**

Index Terms—**in wheel-motor drive electric vehicle, ASR, self-adaptive sliding mode control.**

I. INTRODUCTION

The configuration of electronic stability control system (ESC) such as antilock brake systems (ABS) and acceleration slip regulation systems (ASR) in conventional internal combustion engine vehicles (ICEVs) has significantly improved vehicle safety and maneuverability. Since the electric vehicles (EVs) are the developing trend in the future because of the sustainable development demand and also due to its unique peculiarities and advantages which ICEVs don't have, the stability control strategies for EVs are attracting more and more research effort both from academies and corporations.

The in-wheel-motor drive electric vehicle (IWEV) possesses compact structures and thus yields high drive efficiency, it develops quickly as a typical type of EV, it has the following remarkable features:

1) More accessible information. In contrast with ICEVs, the motor torque can be obtained more easily in IWEVs, and it can be precisely controlled according to the electric current, therefore it is easier to realize the control strategies;

2) Quick response. The response time is generally in the magnitude of 10ms, while for the ICEVs it is much larger due to the complicated mechanic structure and the hydraulic system;

3) Simple simulation models. This provides convenience for the validation of the algorithm.

There are diverse strategies being applied to control the traction forces in EVs. In [1]-[4], the model following control (MFC) strategy and optimal slip control (OSC) is proposed and validated, the MFC effect based on the accuracy of the nominal model and the OSC depends on the estimation of road. In [5], a PID control is proposed. This method could regulate the slip ratio to a preset value. In [6] proposed a method of maximum transmissible torque based on a sliding mode observer, the traction torque is controlled under the maximum transmissible torque. In [7] sliding mode control (SMC) is proposed for traction control and being validated.

Since it is well known for its robustness against parametric and modeling error, a new strategy is designed in this paper based on SMC, it is different from previous methods because it can automatically adapt to different roads without road estimation.

II. WHEEL SLIP DYNAMICS

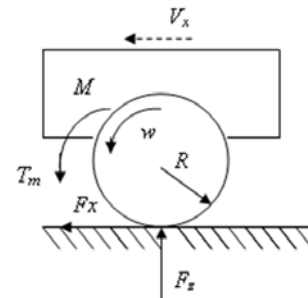The dynamics of a wheel during traction is modeled as Fig 1.

Fig. 1. Single wheel model

$$M \dot{V} = F_x \tag{1}$$

$$I_w \dot{\omega} = T_m - F_x R \tag{2}$$

$$\lambda = \frac{\omega R - V}{\omega R} \tag{3}$$

Where M denotes 1/4 vehicle mass, kg, V_x represents the longitudinal velocity, m/s; F_x is the longitudinal road friction force, N; I_w is the wheel rotational inertia, kg·m^2; ω is the angular rotational speed of wheel, rad/s; T_m represents the traction torque generated by the motor, N·m; R is the wheel radius, m; λ is the generally denoted slip ratio when traction.

Fig 2 shows the typical tire-road friction coefficient as a function of the slip ratio. Although slip slope and the value of optimal slip ratio vary with the road conditions (dry, wet or icy), road type (asphalt, concrete, gravel, or earth), tire types, and many other factors, the shape of the curve is similar, in all conditions the slope of the longitudinal static curve is first increasing in stable region and then decreasing in the unstable region.
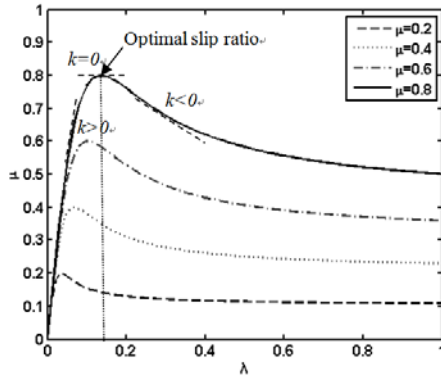

Fig. 2. Longitudinal static curve of tire

III. DESIGN OF SLIDING MODE CONTROLLER

A. Sliding mode control in ASR

This control method is aim to regulate the slip ratio to a default reference value, the value is usually set based on experience and calibrated by road experiments.

The switching function is chosen as

$$m(t) = \dot{e} + Ce = \dot{\lambda} + C(\lambda - \lambda_r) \tag{4}$$

Where λ_r the preset optimum value of slip ratio, C is a constant as undetermined coefficient.

Constitute the phase plane with slip ratio and its derivative, and then the sliding face is described in figure 3. Sliding mode control is to choose appropriate control variables to assure the phase trajectory move along the switching line to its control target $(\lambda_r, 0)$.
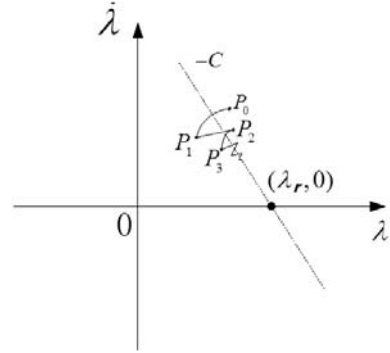

Fig. 3. Sliding control phase diagram

When the state of the system reaches the sliding surface $m(t) = 0$, the system dynamic reads

$$\dot{\lambda} + C(\lambda - \lambda_r) = 0 \tag{5}$$

From (3)

$$\dot{\lambda} = \frac{1}{\omega R}\left[-\dot{V} + (1-\lambda)\dot{\omega}R\right] \tag{6}$$

$$\ddot{\lambda} = \frac{1}{\omega R}\left[-\ddot{V} - (1-\lambda)\ddot{\omega}R - 2R\dot{\omega}\dot{\lambda}\right] \tag{7}$$

Assume that $\dot{v} = \mu g$, from (6) (7) we have

$$\dot{\lambda} = \frac{1}{\omega R}\left[-\mu g + \frac{(1-\lambda)R}{I_w}(T_M - \mu NR)\right] \tag{8}$$

$$\ddot{\lambda} = \frac{1}{\omega R}\left[-\dot{\mu}g + \frac{(1-\lambda)R}{I_w}(\dot{T}_M - \dot{\mu}NR) + \frac{2R}{I_w}(T_M - \mu NR)\dot{\lambda}\right] \tag{9}$$

Where μ is the utilize friction coefficient, equal to the longitudinal force divided by the vertical load, g is the gravity acceleration, m/s^2, N is tire load.

To ensure the sliding surface is reached in finite time, we require:

1) When $m(\lambda) > 0$,

$$\dot{m}(\lambda) = \ddot{\lambda} + C\dot{\lambda} < 0 \tag{10}$$

2) When $m(\lambda) < 0$,

$$\dot{m}(\lambda) = \ddot{\lambda} + C\dot{\lambda} > 0 \tag{11}$$

Consider equation (4) (8) and (9)

$$\begin{aligned}\dot{m}(t) &= \ddot{\lambda} + C\dot{\lambda} \\ &= \frac{1-\lambda}{I_w\omega}(\dot{T}_M - b_1\dot{\mu} + b_2T_M - b_3T_M^2 - b_4\mu - b_5\mu^2)\end{aligned} \tag{12}$$

Where

$$b_1 = \frac{I_w g}{R(1-\lambda)} + NR \tag{13}$$

$$b_2 = \frac{2\mu g}{R(1-\lambda)\omega} + \frac{4R\mu N}{I_w\omega} + C \tag{14}$$

$$b_3 = \frac{2}{I_w \omega} \tag{15}$$

$$b_4 = \frac{CgI_w}{R(1-\lambda)} + CNR \tag{16}$$

$$b_5 = \frac{2Ng}{(1-\lambda)\omega} + \frac{2N^2R^2}{I_w\omega} \tag{17}$$

Then we use constant approaching rate method to calculate the drive torque.

1) When $m(t) > 0$,

$$\dot{m}(t) = \ddot{\lambda} + C\dot{\lambda} = -\varepsilon < 0 \tag{18}$$

Where ε is the approaching rate ($\varepsilon > 0$)

From (12) (18)

$$\dot{T}_M^+ = -\frac{I_w\omega\varepsilon}{1-\lambda} + b_1\dot{\mu} - b_2 T_M^2 + b_3 T_M + b_4\mu + b_5\mu^2 \tag{19}$$

2) When $m(t) < 0$,

$$\dot{T}_M^- = \frac{I_w\omega\varepsilon}{1-\lambda} + b_1\dot{\mu} - b_2 T_M + b_3 T_M^2 + b_4\mu + b_5\mu^2 \tag{20}$$

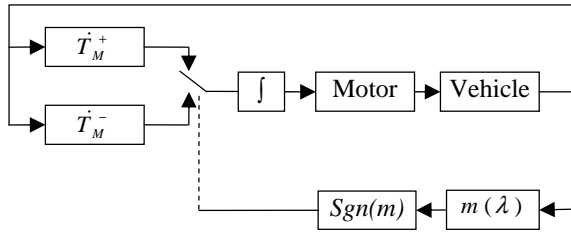The control block diagram is designed as follows.

Fig. 4. SMC block diagram

The control scheme developed in this paper is validated by using (via simulation) Matlab/Simulink. A full vehicle model of 7 state variables is developed in Simulink. The state variables are the side-slip angle, vehicle yaw rate, longitudinal velocity and the angular speed of four wheels. We use Magic Formula to determine the tire forces in the simulation model. The vehicle is assumed to be driven by four in-wheel-motors.
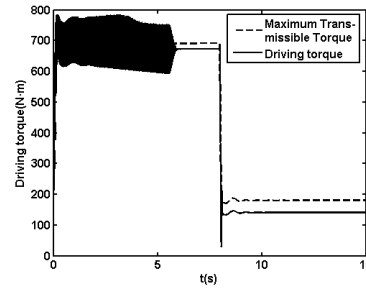
The simulation is carried out on longitudinal split road of friction coefficient changes from $\mu_r = 0.8$ to $\mu_r = 0.2$ at the 8th second. Simulation results are as follows.
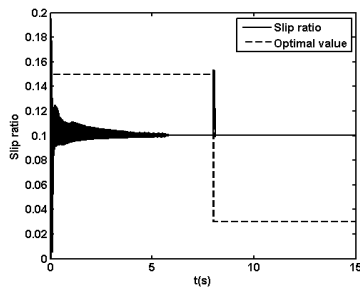
(a) Slip ratio
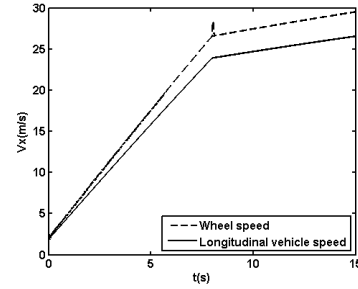
(b) Longitudinal vehicle speed

(c) Driving torque

Fig. 5.Simulation results on longitudinal split road

The slip ratio, longitudinal vehicle speed and driving torque are shown in fig 5. The results show that this method could regulate the slip ratio to a fixed value and it works well on specific roads.

B. Self-adaptive sliding mode controller

The method mentioned above acts well when the roads condition is given, namely when the road friction coefficient is given. When the road condition changes, the optimum slip ratio is changed accordingly, however the control strategy still tracks the same value, this may leads to instability and long driving distance. To avoid such consequences, it needs to be combined with a road estimation block. Since the road friction coefficient estimation error can be amplified when applied to traction control, another algorithm based on SMC is proposed in the following part to achieve better control performance.

Refer to the characteristics of the longitudinal static curve of tire discussed in part I, here we designed another method to seek the optimal slip ratio automatically, thus this method is self-adaptive to different road conditions.

From Fig 2, we build the following logic diagram:

When $k > \theta$, $\lambda < \lambda_r$, increase the drive torque to push λ towards its optimal value;

When $|k| < \theta$, $\lambda \approx \lambda_r$, λ is very close to the optimal value, maintaining the current driving torque;

When $k < -\theta$, $\lambda > \lambda_r$, λ is larger than the ideal value, decrease the traction torque to avoid instability.

Since it is hard to maintain the slip rate at the optimal point, we just limit it to a small region around the optimal value, thus θ ($\theta > 0$) is set as the thickness of the boundary layer.

From expression (2) (3), we have

$$\mu = \frac{T_m - I_w \dot{\omega}}{F_Z R} \tag{21}$$

$$\frac{d\mu}{dt} = \frac{\dot{T}_m - I_w \ddot{\omega}}{F_Z R} \tag{22}$$

With (6), the slope of this curve is

$$\frac{d\mu}{d\lambda} = \frac{d\mu/dt}{d\lambda/dt} = \frac{\omega^2}{F_Z} \cdot \frac{\dot{T}_m - I_\omega \ddot{\omega}}{\dot{v}\omega - v\dot{\omega}} \tag{23}$$

We can find that there are two order derivative of rotational wheel speed in slope calculation, and this should be avoided in control algorithm, because there are noises in speed feedback and it will be enlarged after derivation. Thus we made an improvement to the slope calculation method.

The slope estimation is based on $d\mu/d\lambda$, where the μ and λ is obtained by the speed signal and its time-differentiation. The method uses SMC to regulate the slip ratio to a reference value ,which is updated in real time. In a certain small slip range, the correlation between μ and λ has a linear characteristic. The initial reference value of slip ratio is preset as λ_i, and then it uses the latest 5 value of μ and λ to calculate the slope according to the method of least squares. When the calculated slope is larger than the threshold θ, add a small increment Δ to the current slip ratio to obtain the reference value, when the slope is smaller than $-\theta$, minus a Δ from the reference value, otherwise maintaining the current reference value. In order to increase the convergence rate, a flag is also add to this method, when the calculated μ is relatively stable, the flag will be activated and the current slip ratio is considered as the optimal value. When the road condition changes, the flag will be deactivated and the searching for optimal slip ratio starts again. The control scheme is designed as in Fig.5.
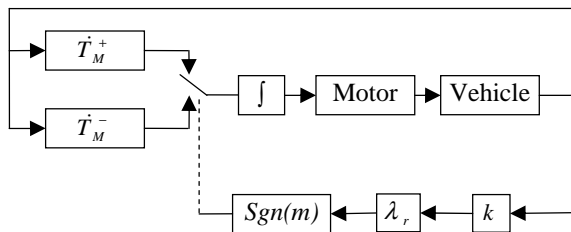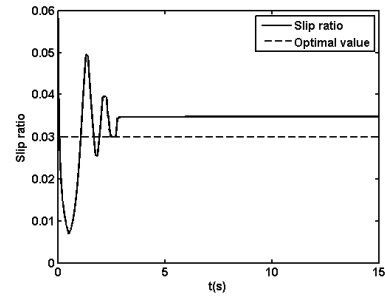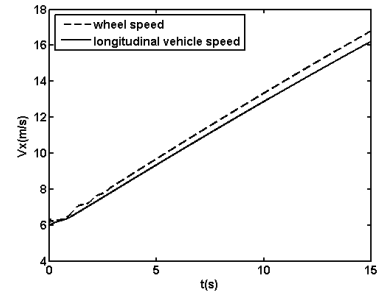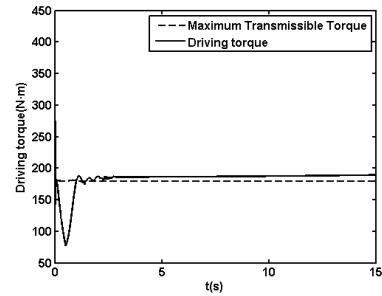
Fig. 6. SMC block diagram

Simulations were carried on road μ_r =0.2, and longitudinal split road μ_r changes from 0.8 to 0.2 at the 8th second.
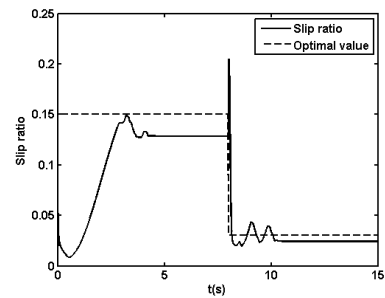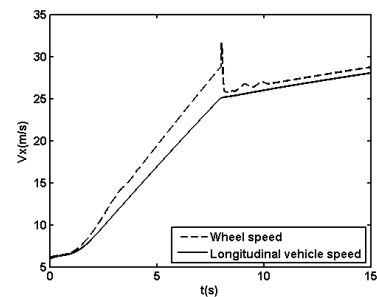
(a) Slip ratio

(b) Longitudinal vehicle speed

(c) Driving torque

Fig. 7. Simulation results on the road with μ_r =0.2

(a) Slip ratio

(b) Longitudinal vehicle speed
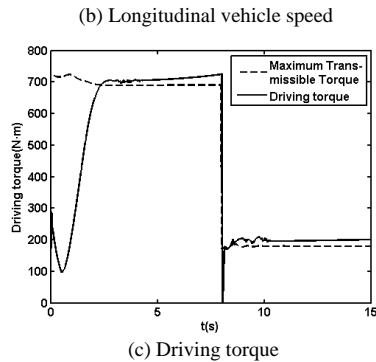

(c) Driving torque

Fig. 8. Simulation results on longitudinal split road

From Fig (7) and (8), we found this sliding mode controller can regulate the slip ratio very close to the optimal value. That means both the longitudinal adhesion force and the lateral adhesion force can be fully made use of. When the tire-road friction coefficient decreases suddenly, the controller can quickly find the optimal slip ratio again.

IV. CONCLUSION

This paper proposed two kinds of sliding mode controller. The first one relies on the identification of road; the control displays good performance when the road condition is known. However, the identification of the road limits the usage. The other kind of controller is capable of automatically searching for the optimal slip ratio and updating the reference slip ratio accordingly. Simulations carried out by using Simulink\Matlab show that it can regulate the slip ratio to a value very close to the optimum slip, thus it is self-adaptive to roads of different friction coefficients without a road estimation block. It can avoid large slip on low friction road and enhance driving efficiency on high friction road.

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