Back-EMF based Slip Prevention Controller for EV utilizing Characteristics of DC Motor

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Abstract: In this paper, a novel slip prevention controller with a load torque disturbance observer using the signal of back EMF is proposed. When slip occurs, the equivalent inertia of EV system will change, and the acceleration of the drive wheels will also change. By constructing an observer, the value of the back EMF is acquired, which includes the information of wheel speed. Then a load torque observer is designed using the signal of back EMF to limit the torque (current) command, and keep the status of EV within a safe area. By selecting observer gain properly, the torque reduction can be adjusted freely in some range. The experimental results of the slip phenomenon simulator utilizing Motor-Generator set verified the effectiveness of the proposed approach.

Keywords: EV, skid prevention, adhesion control, ABS, back EMF

1 INTRODUCTION

Recently more and more electric vehicles (EV), fuel cell vehicles and hybrid vehicles have been developed to solve the air pollution problems in cities caused by the traditional internal combustion engine vehicles (ICV). However, most of them have not yet utilized the most remarkable advantage of EV: Electric motor torque can be controlled much more quickly and precisely than that of internal combustion engine. And because the adhesion characteristics between tire and road surface are greatly affected by the control of traction motor, so the stability and safety of vehicle can be improved by motor torque control. At the same time, if the adhesion status can be controlled effectively, the energy loss will be cut down, and the range of one battery charge will be also expanded.

In order to acquire better adhesion performance for any type of road conditions, the slip prevention controller is necessary to be designed. The slip caused by accelerating, decelerating or braking usually leads to unsafe motion in vehicle driving. For preventing the slip, many technologies are developed such as Model Following Control (MFC) [1],[2], optimal slip ratio control[3]. Sliding mode measurement feedback control[4], and slip ratio fuzzy control[5] also has fine results for slip control. Current disturbance observer also be used to limit the fast increasing of the wheel speed[6]. The slip controllers based on disturbance observer[7] or road conditions estimator[2],[8] are also studied recently. In most of these control algorithms, the wheel speed, even the vehicle speed is needed. In this paper, a novel algorithm of back-EMF based slip prevention controller is proposed. Based on the characteristic of the back EMF, a new disturbance observer is set up. It can follow the input command of current, and when slip occurs, the output torque will be decreased quickly to prevent increasing slip.

2 VEHICLE DYNAMIC MODEL

The problem of wheel slip control can be analyzed by using a one-wheel-car model[4] as shown in Fig.1. There are two inertias in this system, the rotating wheel and the body of the car. The dynamic equation of the system can be expressed as

$$\dot{\omega} = \frac{T - F_d r - F_w(\omega) r}{J_w} \qquad (1)$$

$$\dot{V} = \frac{F_d - F_V(V)}{M} \qquad (2)$$

where T is the sum of driving and braking torques, i.e. $T = T_d - T_b$; F_d is the drive force of the chassis, F_w is the average friction force of the driving wheels for acceleration and the average friction force of all wheels for deceleration. F_V is the wind force of the vehicle. M is the mass of the chassis and the wheels of the vehicle, i.e. $M = M_v + M_w$.

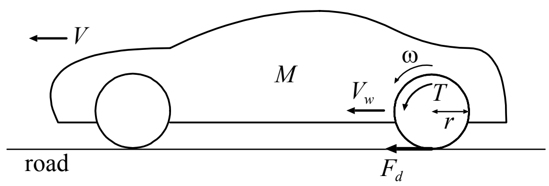

Fig.1 One-wheel vehicle model

The slip ratio λ is used to describe the slip status between the road and the tire. It is defined as

$$\lambda = \frac{\omega r - V}{\omega r} \quad \text{(Driving)} \tag{3}$$

or

$$\lambda = \frac{\omega r - V}{V} \quad \text{(Braking)} \tag{4}$$

The friction coefficient μ is a function of λ, $\mu = f(\lambda)$, which is dependent to the road condition. For simulating the road status, the following function of $\mu - \lambda$ will be used in this paper.

$$\begin{aligned} \mu &= -1.05ke^{-45\lambda} + ke^{-0.45\lambda} \text{(driving)} \\ \mu &= 1.05ke^{35\lambda} - ke^{0.35\lambda} \text{(breaking)} \end{aligned} \tag{5}$$

where

$$k = \begin{cases} 1.0 & \text{(dry road)} \\ 0.2 & \text{(ice road)} \end{cases}$$

The $\mu - \lambda$ curve is shown in Fig.2.

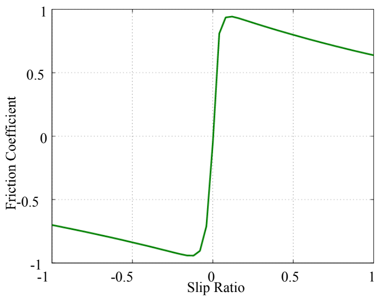

Fig. 2 The μ–λ curve

The drive force of the vehicle F_d is proportional with the friction coefficient and the pressure to road.

$$F_d = N\mu(\lambda) \tag{6}$$

where N is the normal component of reactive effect on tires. The block diagram of the vehicle is shown in Fig.3.

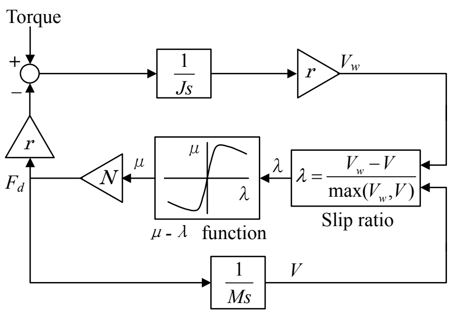

Fig. 3 The block diagram of the vehicle

3 THE SLIP PREVENTION SCHEME UTILIZING THE CHARACTERISTIC OF BACK-EMF

3.1 Back EMF Observer

In the condition of no speed sensor, the slip prevention controller can also be realized with other signals such as back EMF. This kind of slip controller has more reliability and more robust performance. But the signal of back EMF cannot be detected directly, it is necessary to set up an observer to estimate the value of back EMF. A current disturbance observer with variable gain and time constant is discussed in paper [6], which utilized the torque drop characteristic to limit the torque when slip occurs. The current disturbance observer is used to compensate the voltage drop caused by back EMF, so in fact it is also a back EMF observer. In this paper it is employed to estimate the back EMF, as shown in Fig.4.

The estimated back EMF can be expressed as

$$\hat{V}_{emf} = \frac{u^* - (Ls + R)i}{\tau s + 1} \tag{7}$$

where the $\frac{1}{\tau s + 1}$ is a low-pass filter for restraining the noise of the estimated value.

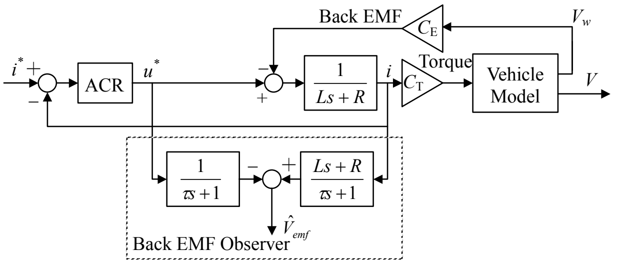

Fig.4 The block diagram of the EV system

In the inner loop of the controller, an appropriate current regulator (ACR) is designed to follow the current command quickly.

3.2 The Slip Prevention Scheme Based on Load Torque Observer with Back EMF

It is well known that the value of back EMF is proportional with the motor speed, (7) can be written as

$$V_i = \omega C_E \frac{1}{\tau s + 1} \tag{8}$$

So it is possible to construct a load torque observer based on the output of current disturbance observer, as shown in Fig.5, where $C^2 = C_E * C_E$. By this approach, the load torque disturbance can be observed without speed sensor. In Fig.5, as the current is proportional with the torque, the load torque can be expressed by its current i_L, and i_d is the drive current corresponding to the drive force F_d.

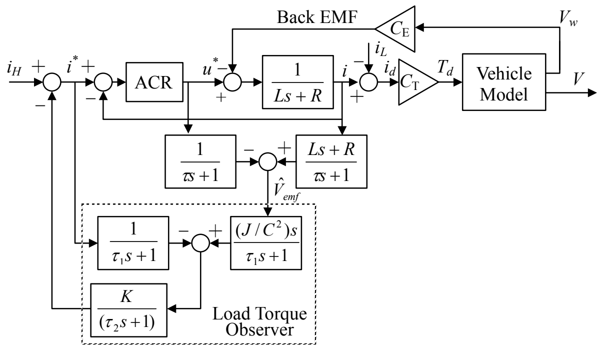

Fig.5 Slip prevention system based on load torque observer

As the time constant of the inner loop is more than 10 times as small as that of the outer loop, in order to simplify the analysis of the system dynamics, the transfer function from i^* to i is considered as 1. Thus the open loop transfer function from human drive command i_H to the drive current i_d is

$$G_{OL} = \frac{K}{(\tau_1 s + 1)(\tau_2 s + 1) - K} \tag{9}$$

Drawing the Bode diagram of the open transfer function as shown in Fig.6, the dynamics of the system can be analyzed as following.

The Bode diagram shows that, when K ≤ 1, the gain margin and phase margin are big enough, but when K>1, due to the small stability margin, the system will have poor robust performance against uncertainty in low and high frequency parts.

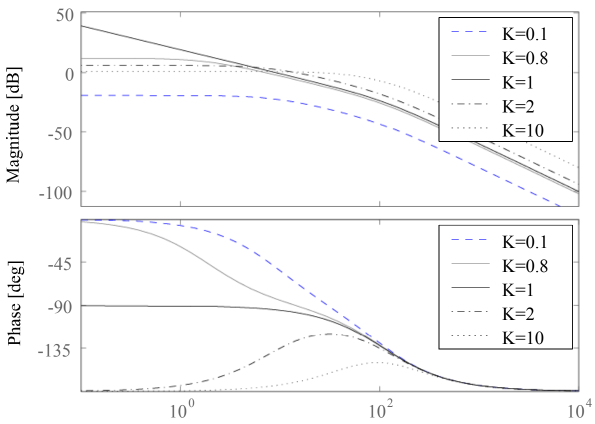

Fig.6 Bode diagram of the system

The closed loop transfer function from i_H to i_d is

$$G_{CL} = \frac{(\tau_1 s + 1)(\tau_2 s + 1)}{(\tau_1 s + 1)(\tau_2 s + 1) + K(J_n / J - 1)} \tag{10}$$

It indicates that, when $J = J_n$, the closed loop transfer function will be equal to 1, that is, the current command, i.e. the torque command will be exactly realized by the controller. And if slip happens, the inertia J will decrease, and the transfer function will also decrease with the change of J. On the other hand, when J increases, the transfer function will also increase to keep the acceleration as a constant value.

4 SIMULATION AND EXPERIMENT RESULTS

Suppose that the vehicle is running from the dry road to the icy road, and the surface of the icy road is very smooth, so that the friction between the tire and the road rapidly reduces. At the same time, if the motor of the EV is still keeping the driving torque as before, then the wheel will slip on the icy road quickly.

The slip phenomenon is simulated by MATLAB utilizing the EV system as shown in Figs.3 and 5. Suppose the EV starts to accelerate on the dry road from t = 0[sec], and at t = 3[sec] it enters the icy road. The parameters of the EV system are used with the ones of "UOT March I" which is the experimental EV of our laboratory. In order to compare with the experiment, the simulation outputs are proportionally converted into the scope of the experiment results.

4.1 Simulation Results

In order to find the relationship between the performance of the slip controller and the gain of the load torque observer K, the gain is changed from 0 to 10. The simulation results are shown in Fig.7. In Fig.7 (a) and (c), when K = 0, the wheel speed dramatically increases after slip occurred. When K = 1, the acceleration always keep the constant value, the fast increase of the speed is limited. When K > 1, the wheel speed is decreased after slip happened. The torque and the output of the observer shown in Fig.7(b) and (d) also proved this point. So the slip ratio is limited as the K increases as shown in Fig.7(e).

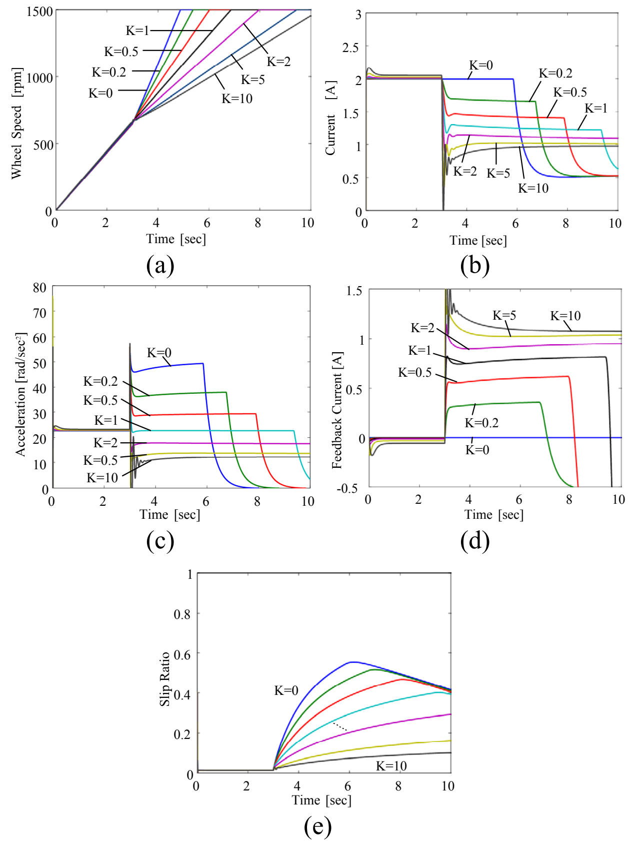

Fig.7 Simulation results of the proposed controller

4.2 Experiment Results

In this paper, the DC Motor-Generator system, as shown in Fig.8, is designed to simulate the EV system with slip phenomenon. The block diagram is shown in Fig.9. In the M-G set, the drive motor and the load motor can be controlled independently. And an inertia simulator is designed to simulate the varying of the equivalent inertia of the EV system.

The experiment results are shown in Fig.10. The curves have the same features with the ones of simulation results shown in Fig.7 except for some noises. With the increase of K, the acceleration, as well as the slip ratio, is limited effectively.

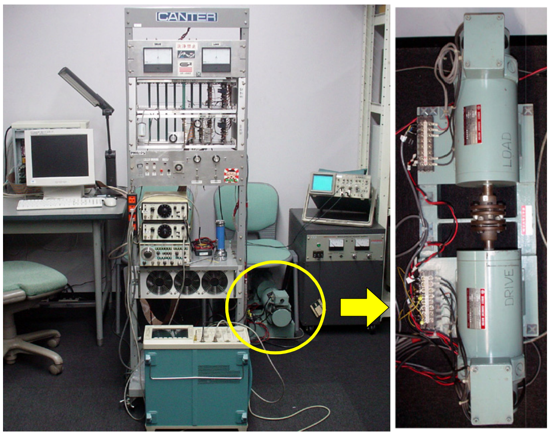

Fig.8 Experimental system

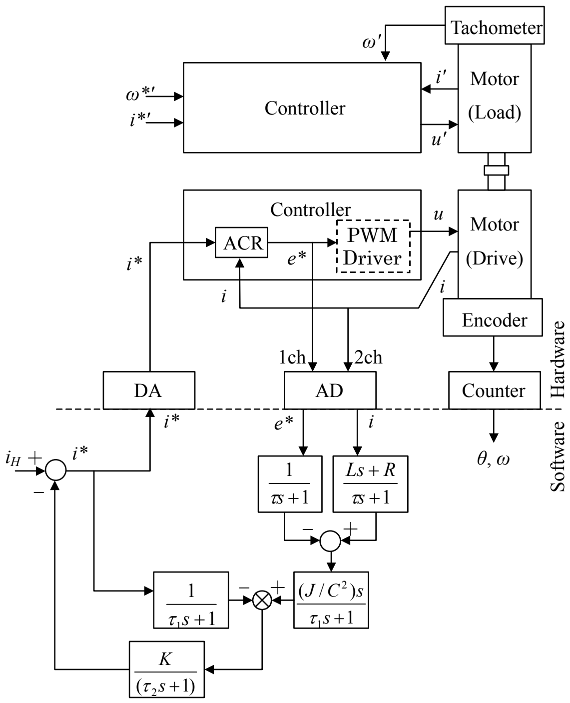

Fig.9 Block diagram of experimental system

5 CONCLUSION

By using the signal of back EMF, the novel slip prevention controller does not need the wheel encoder, and enhances the reliability of the slip prevention system. The response time of the slip controller can be limited in 0.1[sec] according to the experiments. The simulation and experiment prove that the torque reduction of the back-EMF based controller can prevent the slip phenomenon effectively, especially in process of traction control.

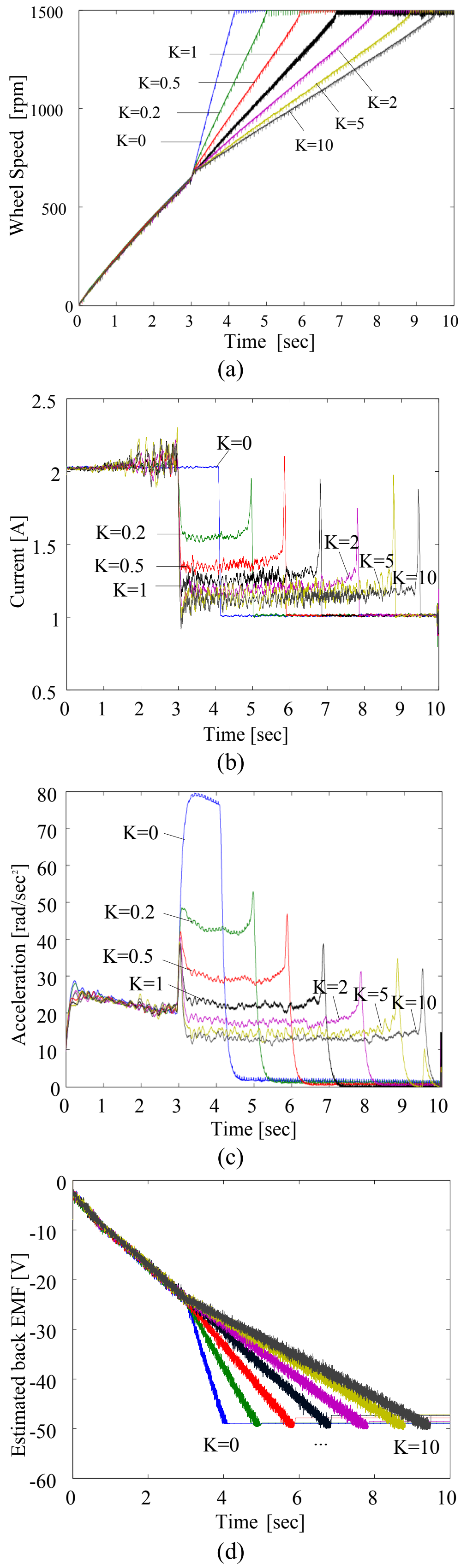

Fig.10 Experimental results

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