Design and Test of a Novel Skid-Prevention Controller based EV Simulator

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***Abstract*—In this paper, a simulator of one-wheel EV system is designed for testing of slip prevention controller by using M-G set. The drive motor of the M-G set is used to simulate the drive wheel of the EV, and the load motor is used to simulate the load force of the chassis. In driving process, the torque of the load motor will be changed according to the drive force of the chassis that is calculated by the program. So it can simulate the dynamic process of the tire-road system. Based on this simulator system, a novel slip controller with inertia regulator is proposed and tested. The simulation results simulated by MATLAB and the experiment results have the same features and the results verified the simulating performance of the M-G system. And the experiment results proved the validity of the slip controller.**

I. Introduction

The Adhesion characteristics between tire and road surface has great effect on the driving and braking control of the vehicle. In order to acquire high-performance motion characteristic, the traction force of engine or motor should be regulated to keep a nice adhesion status. This means that the vehicle stability and safety can be improved by drive torque controlling. 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], [6], optimal slip ratio control[2]. Sliding mode measurement feedback control[3], and slip ratio fuzzy control[4] also has fine results for slip control. Current disturbance observer also be used to limit the fast increasing of the wheel speed[5]. The slip controllers based on disturbance observer[7] or road conditions estimator[2], [8] are also studied recently. In this paper a novel controller scheme based on an observer of inertia moment is proposed.

In fact, the testing of skid controller is difficult and expensive. Commonly, real vehicle and real slippy road and other expensive equipments are needed to test the validity of a slip controller. In this paper, a simulator of one-wheel EV system is designed for testing of slip prevention controller by using M-G set. The drive motor of the M-G setup is used to simulate the drive wheel of the EV, and the load motor is used to simulate the load force of the chassis. In driving process, the torque of the load motor will be changed according to the drive force of the chassis that is calculated by the program. So it can simulate the dynamic process of the tire-road system. Based on this simulator system, a novel slip control method is proposed and tested. The simulation results simulated by MATLAB and the experiment results have the same features and the results verified the simulating performance of the M-G system. And the experiment results proved the validity of the slip controller.

II. Vehicle Dynamic Model

The problem of wheel slip control can be analyzed by using a one-wheel-car model[3] 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

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

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

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. $M = M_v + M_w$.

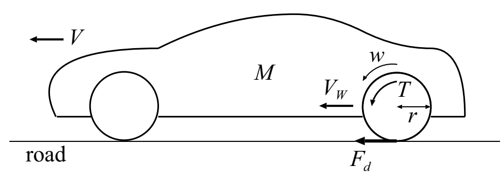


Fig. 1. One-wheel vehicle model.

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

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

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

where V_W is the wheel speed, V is the velocity of the chassis.

The friction coefficient μ is a function of slip ratio λ, $\mu = f(\lambda)$, which is dependent on the road conditions. For different conditions of the road such as dry, wet, snowy, etc., the relationship between λ and μ is different.

The drive force of the vehicle F_d is proportional with the friction coefficient and the pressure to road.After having achieved the friction coefficient μ from slip ratio λ utilizing $\mu - \lambda$ curve, the driving force F_d can be calculated by

$$F_d = N\mu(\lambda) \tag{5}$$

where N is the normal component of reactive effect on tires. The block diagram of the vehicle is shown in Fig.2.

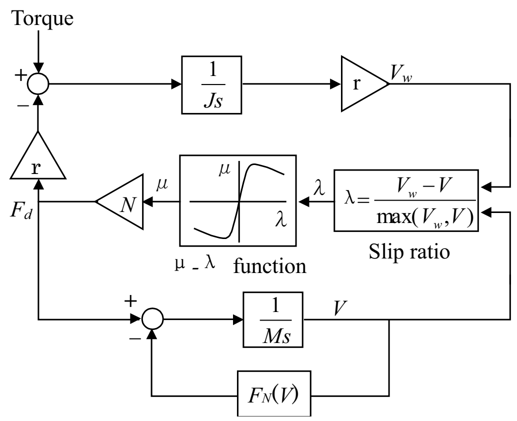


Fig. 2. The block diagram of the vehicle.

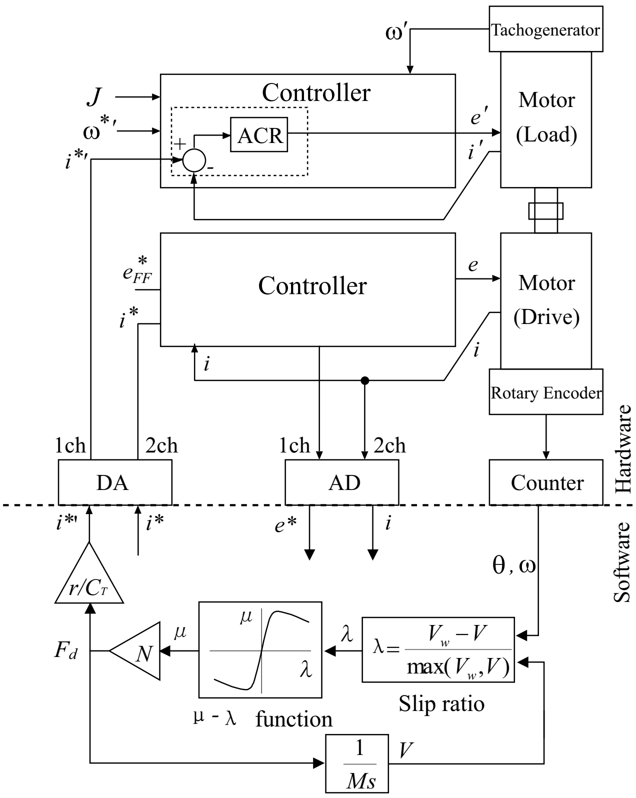


Fig. 3. The block diagram of the vehicle simulator based on M-G set.

III. The Wheel Dynamic Simulator utilizing M-G setup

Based on the block diagram shown in Fig.2, the vehicle simulator using of M-G set can be designed as shown in Fig.3. The slip ratio λ of the vehicle system can be calculated by the speed of the wheel and the chassis. And according to the simulated road status, such as dry, wet, or icy road, ramp road, and so on, the friction coefficient and the load torque, as well as the load current can be calculated.

For four kinds of conditions, (A) Normal asphalt road, (B) Slippy road, (C) Ramp Up Road, (D) Ramp Down Road , the Vehicle simulator is tested, and the experiment results are shown in Fig.4.

The parameters, such as inertia moment of the wheel and the chassis, can be adjusted freely to adapt different vehicle parameters. At the same time, other friction and wind resistance can also be simulated by the system. In this paper, these disturbances are ignored in simulation and experiment.

IV. Design of Slip Controller with Inertia Regulator

A. Estimating of the acceleration based on 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 [5], 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, and using the signal of back EMF, the acceleration also can be acquired as shown in Fig.5.

The estimated back EMF can be expressed as

$$\hat{V}_{emf} = \frac{u^* - (Ls + R)i}{\tau s + 1} \tag{6}$$

The acceleration can be expressed as

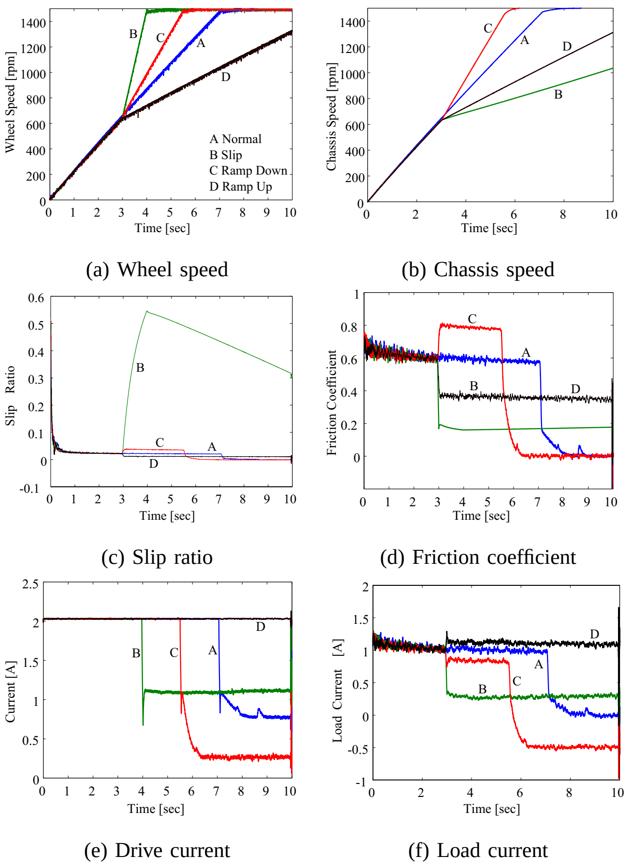
$$\hat{a} = \frac{\hat{V}_{emf}(J/C^2)s}{\tau_1 s + 1} \tag{7}$$

where the $\frac{1}{\tau s+1}$ and $\frac{1}{\tau_1 s+1}$ is a low-pass filter for restraining the noise of the estimated value.

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

B. Slip controller Based on Load Torque Observer

With the necessary information of acceleration, it is possible to construct a load torque observer, as shown in Fig.5. By this approach, the load torque disturbance can



(a) Wheel speed (b) Chassis speed

(c) Slip ratio (d) Friction coefficient

(e) Drive current (f) Load current

Fig. 4. Experiment results of the vehicle simulator with different conditions

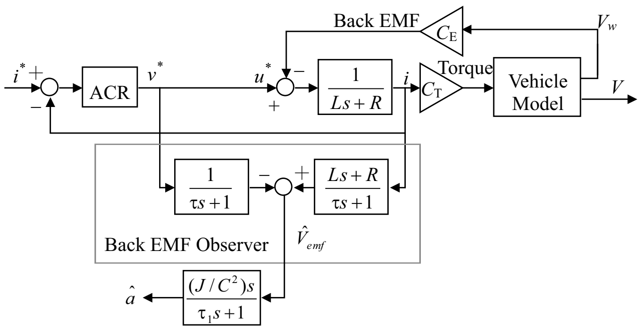


Fig. 5. The acceleration Observer.

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 motivate current of F_d.

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 dynamic analysis of the system, 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

$$G_{OL} = \frac{K}{(\tau_1 s + 1)(\tau_2 s + 1) - K} \tag{8}$$

Drawing the Bode diagram of the open transfer function

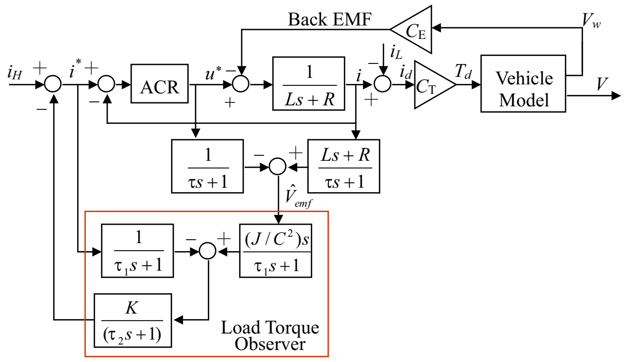


Fig. 6. Slip prevention system based on load disturbance observer.

as shown in Fig.7, 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.

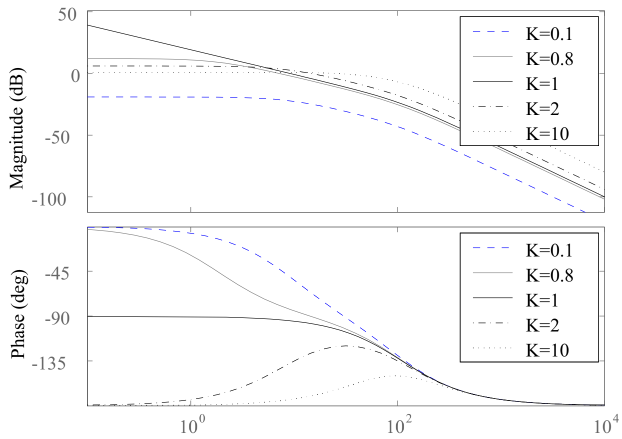


Fig. 7. Bode diagram of the slip controller based on load torque observer.

The closed loop transfer function from i_H to i_d is

$$G_{CL} = \frac{(\tau_1 s + 1)(\tau_2 s + 1)}{(\tau_1 s + 1)(\tau_2 s + 1) + K(J_n/J - 1)} \tag{9}$$

It indicates that, when $J = J_n$, the closed loop transfer function will be equal to 1, that is, the current command, i.e. current (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.

By these analysis, the K is better to be kept within 1. In this condition, the controller can maintain the given acceleration but it also lead to slip.

C. Slip controller with inertia regulator

In order to limit the torque output after slip occurred, additional regulator is tried to introduced into the system.

When the slip occurs, the equivalent inertia of the system will decrease. Using this characteristic, it is possible to set up a inertia observer. By analyzing the dynamic of the inertia, it is found that before the slip controller is activated, the decrease of the inertia depends on the decrease of the frictional coefficient μ. That is, if the μ is smaller, then the inertia is also smaller. So based on a inertia observer, a new regulator can be added to the system to adjudge the slip status of the vehicle.

The block diagram slip controller with inertia regulator is shown in Fig.8. Where the regulator Q can be designed as a integrator $Q = K_j/s$. Because the inertia of the system is varying while the vehicle is running on the road. So a inertia observer is used to estimate the dynamic inertia of the vehicle. When the inertia drops quickly, the regulator will be activated, and it can record the extent of the slip. Although when the slip is too serious to limit the wheel's acceleration, the inertia regulator also can work to restrain the torque command. And when the adhesion status is recovered, the regulator will fade out.

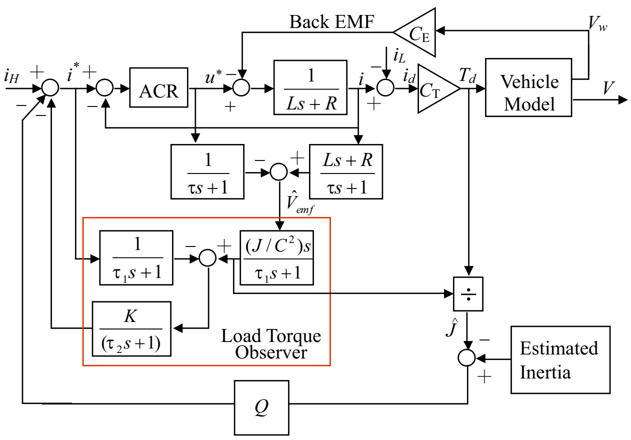


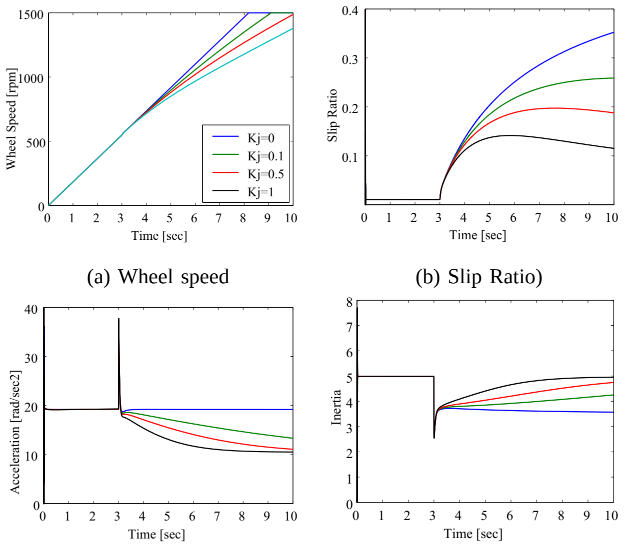
Fig. 8. Block diagram of the inertia regulator.

V. 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.2 and 6. Suppose the EV starts to accelerate on the dry road from $t = 0$, 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.

A. Simulation Results

In order to find the relationship between the slip control performance and the gain K_j, the system is simulated by MATLAB. The results are shown in Fig.9. In Fig.9 (a) and (c), when $K_j = 0$, the acceleration always keep the constant value, with the increase of K_j, the wheel acceleration is decreased after slip happened. The equivalent inertia of the system is shown in Fig.9(d), with the increase of the K_j, its drop also be limited. So the slip ratio is restrained while the K_j increases as shown in Fig.9(b).



(a) Wheel speed (b) Slip Ratio

(c) Acceleration (d) Dynamic Inertia

Fig. 9. Simulation results of the slip controller with inertia regulator

B. Experiments Results

The Motor-Generator system is shown in Fig.10, The block diagram is shown in Fig.11.

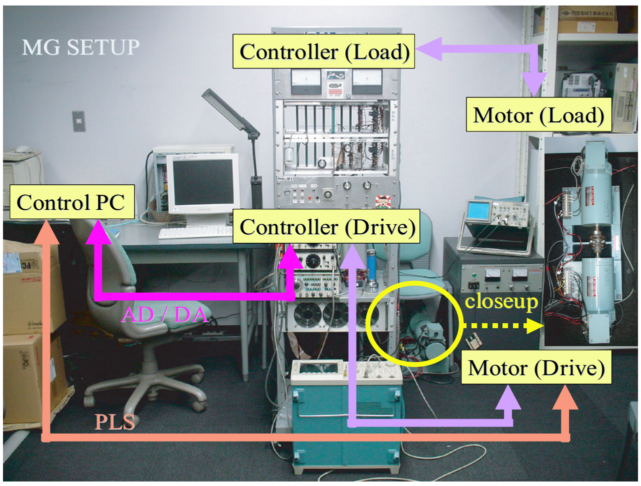


Fig. 10. Experimental system.

The experiment results are shown in Fig.12. The curves have the same features with the ones of simulation results shown in Fig.9 expect for some noises. With the increase

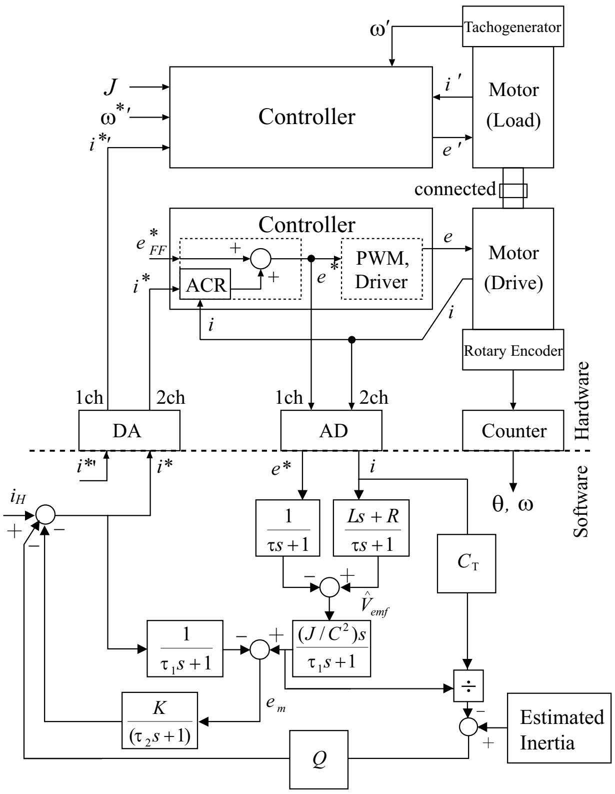
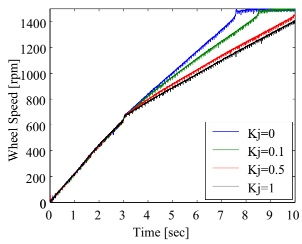
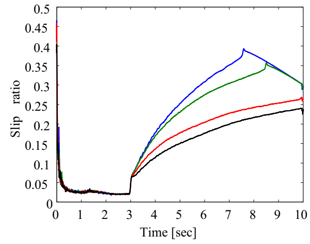


Fig. 11. Block diagram of experimental system.

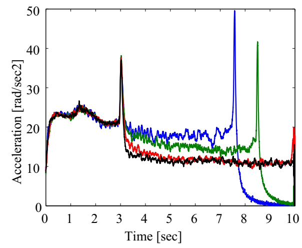
of K_j, the acceleration, as well as the slip ratio, is limited effectively.



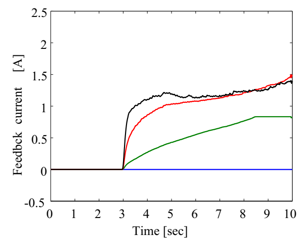
(a) Wheel speed



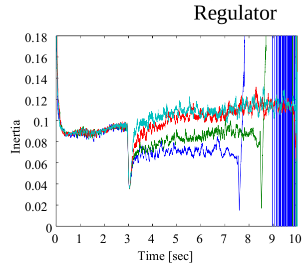
(b) Slip Ratio



(c) Acceleration



(d) Feedback of the Inertia Regulator



(e) Dynamic Inertia

Fig. 12. Experiment result of the slip controller.

VI. Conclusion

By comparing the simulation results and the experiment results, The vehicle slip simulator using M-G setup can be tested easily, and the conditions of the controller and system can adjusted freely. The features of the simulator system has similar features with the real vehicle. And it can be used to verify the slip controller before in-field experiment. The slip controller with inertia regulator proposed in this paper has nice performance in slip control. The simulation and experiment prove its feasibility and validity.

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