Recent Trends of Electric Vehicle Technology

- Motion Control of Electric Vehicle -

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Abstract- The most distinct advantage of electric vehicle is in its quick and precise torque generation. We propose two novel traction control techniques of electric vehicle, i.e., the model following control and the optimal slip ratio control. Their effectiveness is demonstrated by using the test vehicle "UOT Electric March".

I. INTRODUCTION

Recently a lot of electric vehicles (EV) have been developed to solve environment and energy problems caused by the use of internal combustion engine vehicles (ICV). Some of them already have enough performance in practical use. However, they do not yet utilize the most remarkable advantage of EV. Electric motor torque can be controlled much more quickly and precisely than that of internal combustion engine. For example, adhesion characteristics between tire and road surface are greatly affected by the control of traction motor. This means that the vehicle stability and safety can be improved by motor torque control. If we can use special low drag tires with smaller energy loss, the range of one battery charge will be drastically expanded.

In this paper, we will propose some novel traction control techniques, which can be firstly realized only by utilizing electric motor's quick torque response. They are the model following control and the optimal slip ratio control. By using the newly developed test vehicle "UOT Electric March", we will show some successful experimental results. In order to achieve the best control performance, the estimation method of road surface condition is proposed and its realizability is shown also by real experiment.

II. STATE OF THE ART OF ELECTRIC VEHICLES

First of all, I would like to summarize the recent status of electric vehicle. My impression in EVS-13, Osaka and EVS-14, Orlando, are as follows.

(1) Development of practical electric vehicles have been completed.

Driving performance (top speed and acceleration) is already satisfactory. Range of one battery charge exceeds 200km.

(2) Motor selection becomes clear.

In Japan, PM motors (permanent magnet type synchronous motors or blushless DC motors) are taking over IM (induction motors). In-wheel motors are promising although their undamped weight is bigger. In the US, IM (induction motors) are still widely used. IM has advantage for large cars and has better robustness.

(3) Battery trend becomes also clear.

The main flow from Seal-acid, via Nickel Metal-Hydride, to Lithium-ion batteries is now recognized. Fuel-cell battery is thought to be the final target.

(4) Components are almost completed.

Battery charger has two types: inductive and conductive. SOC (State Of Charge) indicator with high reliability is a still important problem.

Table I Major Electric Vehicles Seen in EVS 13 and 14.

maker		TOYOTA	NISSAN	HONDA	GM	FORD
name		RAV4-EV	Altra EV	EV Plus	EV 1	Ranger EV
weight		1540kg	1700kg	1615kg	1350kg	2123kg
seating capacity		5	4	4	2	2
speed		125km/h	120km/h	over 130km/h	130 km/h	120 km/h
range		200km (city) 170km (highway)	200km (city, highway)	210km (10-15 mode)	110km (city) 145km (highway)	95km
motor		PM	PM	PM	IM	IM
Battery	type	Ni-MH	Lithium ion	Ni-MH	Lead acid	Lead acid
	capacity	95A×5h 30V	100A×3h 28.8V	95A×3h 12V	53Ah 12V	86A×3h 8V
	voltage	288V	345V	288V	312V	312V


Toyota RAV4-EV


Nissan Altra EV


Honda EV Plus


GM EV 1


Ford Ranger EV


Luciole（環境庁）

Photo I Major Electric Vehicles Seen in EVS 13 and 14.

The typical "future issues of electric vehicle" are as follows.

(1) A certain quantity of practical EV production

What is most important now is to reduce cost while maintaining performance still high. Various types of EV's are needed. It may be a good idea to make relatively expensive but reliable and attractive cars for rich aged people.

(2) Battery improvement

Development and improvement of battery itself is important, i.e., long life, low cost and extended life-cycle, etc. BMS (Battery Management System) is necessary. Installation is also a problem. BBF (Battery Built-in Frame) proposed in Luciole may be a solution.

(3) Infrastructure construction

If electric power companies have EV batteries as the final part of power delivery and then batteries are not included in car price, EV must be widely sold. It is important to make users to buy EV's.

Of course I agree with these "future issues". But most people are not aware of the most important point of electric vehicle. The most distinct advantage of electric vehicle is in its quick and precise torque generation. If we do not utilize this advantage, EV will never be successful. On the contrary, by utilizing this superiority, EV has the bright future.

III. TRACTION CONTROL - ADVANTAGE OF ELECTRIC VEHICLE -

Traction control is the control to suppress tire slip when the vehicle is accelerating, for example, on icy road. By controlling the traction force, the driving and cornering performance mainly in acceleration are improved.

We should consider two forces acting on the vehicle body, i.e., the driving (longitudinal) and side (lateral) forces. As depicted in Fig.1, these forces depend on the slip ratio λ. λ is defined by eq.(1), where V_w and V are the wheel and vehicle speeds.

$$\lambda = (V_w - V) / V_w \tag{1}$$

The side force takes its maximum value when $\lambda=0$ and becomes smaller for bigger λ. If λ increases by sudden decrease of road friction, the side force gets smaller drastically. This causes serious problems: drift-out in front wheel driven cars, spin in rear wheel driven cars, and drift-out with rotation in four wheel driven cars. Such a loss of cornering force is extremely dangerous. The average traction force is then also decreased.

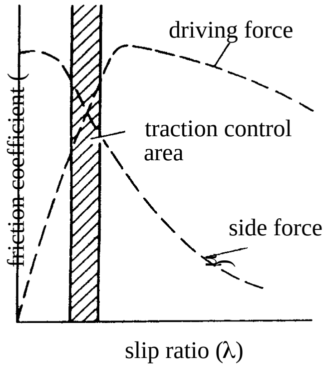


Fig.1. Characteristics of driving and lateral forces.

Traction control can be classified into following two steps:

(1) longitudinal control, for example, the adhesion improvement to prevent slip. This is done by controlling the traction force, and

(2) lateral control, for example, the yaw control to keep the yaw motion to be zero. This is done mainly by controlling the steering angle.

In this paper, we focus our discussion into **(1) longitudinal control**. For the lateral control, the steering angle of the front wheels is the dominant control input. Such technique is already well developed for ICV and the results can be applied to EV in a better improved manner. By applying multi wheel drive system, in particular, the independent control of 4 wheel-in motors, EV can realize completely new motion characteristics.

To realize the effective traction control system, we need a sophisticated mechanism quickly to reduce the excessive driving torque. In ICV, this is realized mainly by the following three techniques.

(1) engine control: Engine torque itself is suppressed. To reduce air supply is the basic technique, but for quicker response, advanced techniques like fuel-cut and spark timing shift are used together.

(2) brake control: Wheel rotation itself can be stopped by braking. This method has quicker response than the engine control. Independent control of left and right tires is effective for μ-split braking. Brake control should be used together with the engine control because brake parts often have thermal problem.

(3) mission control: Driving torque of the slipping tire is transferred to the non-slipping tire. This technique is effective for μ-split road. As the total torque can not be reduced, mission control technique should be applied together with the engine control.

Table II summarizes the advantages and disadvantages of these techniques.

Table II Comparison Of Traction Controls For ICV.

	controllability	response	cost	operation feeling	total
engine control	good	fair	excellent	fair	good
brake control	good	excellent	excellent	poor	fair
mission control	fair	poor	excellent	fair	poor
engine + mission controls	good	fair	good	fair	fair
engine + brake controls	excellent	excellent	good	good	excellent

Electric Vehicle has great advantages as followings for realization of high performance traction control.

(1) low cost: Above mentioned techniques for ICV need additional costly hardware, e.g., throttle and brake actuators. EV does not need anything more. Traction control can be realized only by software. Low cost "basic car" can have high performance traction control.

(2) quick response: In ICV, more than 200[ms] are needed to open the throttle actuator. The actual response time is much longer because the mechanical delay is included. In contrast, the response time of electric motor torque is less than 10[ms].

(3) easy controller design: In ICV, unknown strong non-linearity lies in the transfer characteristics from the control input (for example, air valve angle to engine, oil pressure of brake system, etc.) to the generated torque. This makes it difficult to construct a mathematical model for controller design. In EV, by applying simple current control, the generated torque is exactly proportional to the torque command.

IV. Model Following Control

In this paper, we propose two control strategies: one is the **model following control** (**MFC**), and the other is the **optimal slip ratio control**. MFC is the starting point of our research project of "Control of Electric Vehicle" and its basic feasibility is demonstrated here by real experiment.

A. Principle of MFC

Fig.2 shows the block diagram of the model following control. I_{com} is the current command proportional to the acceleration pedal angle. ω is the rotational speed of the driving shaft. ω increases drastically when the tire slips. Vehicle dynamics including tire characteristics and road surface friction are very complicated, but if we introduce the slip ratio λ, the vehicle body can be seen as one inertia system having the equivalent inertia moment of

$$J = J_w + Mr^2(1-\lambda) \tag{2}$$

Here, J_w , M and r are the shaft inertia moment, vehicle weight and tire radius. Eq.(2) means that, when slip occurs, the vehicle seems lighter. Therefore, we use the following inertia moment with $\lambda=0$ in the reference model.

$$J_{model} = J_w + Mr^2 \tag{3}$$

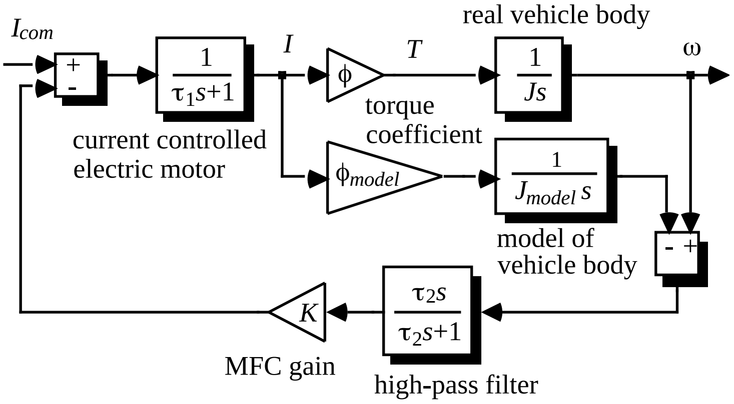


Fig.2. Block diagram of MFC.

When there is no slip, actual J is almost equal to J_{model}. Any signal is not generated from MFC controller. If the tire slips, the actual wheel speed ω increases immediately. The model wheel speed does not increase. By feeding back the speed difference to the motor current command, the actual motor torque is reduced quickly and it induces re-adhesion.

As this control function is needed only in relatively higher frequency region, we used a high pass filter on the feedback pass. In actual implementation, two high pass filters are inserted before taking the difference between actual and model speeds to avoid the offset problem of integrator.

B. Experimental Result of MFC

Fig.3 shows the slip experiment using UOT Electric March. We used iron plates as slippery road surface. Water is scattered to reduce the friction coefficient. The vehicle is accelerated by the constant current command of 300[A]. The feedback gain K in Fig.2 is 30. The front wheels are on the slippery area between t=1.25[s] and 1.7[s].

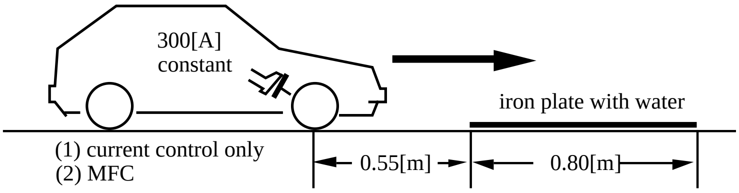
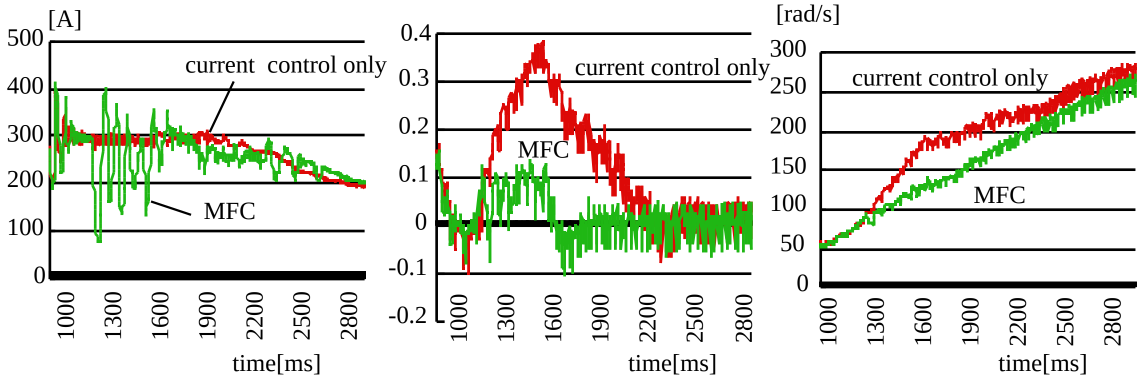


Fig.3. Slip experiment.

Experimental results are shown in Fig.4. We can see that MFC can reduce the motor current effectively when the vehicle goes onto the slippery area, and then the slip ratio is kept much lower comparing to the case of current control only. Some vibration seen in the current waveform in Fig.4(a) should be suppressed in the future.



(a) motor current (b) slip ratio (c) wheel speed

Fig.4. Experimental results of MFC.

V. OPTIMAL SLIP RATIO CONTROL

The model following control is a very rough approach although it has been shown that the motor control is really effective for adhesion improvement. If we want more exactly to regulate the slip ratio within a specified range, more precise approach is necessary. Fig.5 shows the idea of the optimal slip ratio control developed from this viewpoint. When the optimal slip ratio is decided by the road condition estimator, the slip ratio controller receives the command and realizes it.

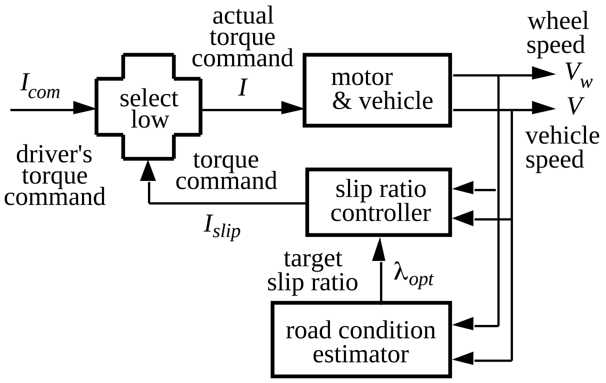


Fig.5. Block diagram of the optimal slip ratio controller.

A. Vehicle Model

We assume that the two motor torques and friction forces are same in left and right, and that the rolling and air frictions are small enough. In Fig.6, the kinematic equations of the wheel and vehicle take the forms of

$$\left(F_m - F_d\right)\frac{1}{M_w s} = V_w \tag{4}$$

and

$$F_d \frac{1}{M s} = V \tag{5}$$

where,

F_m : motor torque (force equivalent)

F_d : friction force

M_w : wheel inertia (mass equivalent)

M : vehicle weight

The friction force between the road and wheel is given by

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

where N is the vertical force given by $N = Mg$.

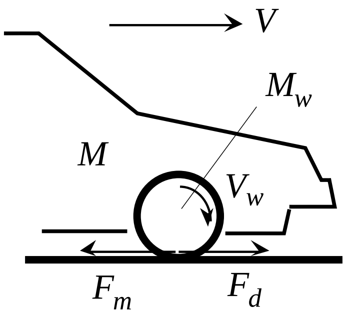


Fig.6. Vehicle model.

From eq.(1), the following perturbation system is derived.

$$\Delta\lambda = \frac{\partial\lambda}{\partial V}\Delta V + \frac{\partial\lambda}{\partial V_w}\Delta V_w = -\frac{1}{V_{w0}}\Delta V + \frac{V_0}{V_{w0}^2}\Delta V_w \tag{7}$$

where V_{w0} and V_0 are the wheel and vehicle speeds at the operational point. The friction force is represented using a, the gradient of $\mu-\lambda$ curve, as

$$\Delta\mu = a\,\Delta\lambda \tag{8}$$

By combining eqs.(7) and (8) with the perturbed forms of eqs. (4) and (5), the transfer function from the motor torque to the slip ratio is finally given by

$$\frac{\Delta\lambda}{\Delta F_m} = \frac{1}{Na}\,\frac{M\,(1-\lambda)}{M_w + M\,(1-\lambda)}\,\frac{1}{1+\tau s} \tag{9}$$

where the time constant τ is given by eq.(10) which is proportional to the wheel speed V_{w0}.

$$\tau = \frac{1}{Na}\,\frac{MM_wV_{w0}}{M_w + M\,(1-\lambda)} \tag{10}$$

The typical value of τ in our experimental vehicle is 150～200[ms] when a=1 and the vehicle speed is around 10[km/h]. Note that a can be negative in the right-hand side of the peak point of $\mu-\lambda$ curve.

B. Design of Slip Ratio Controller

We used a simple PI controller with a variable gain as the slip ratio controller given by eq.(11). Its nominator compensates for the pole of eq.(9). The integral gain is constant and the proportional gain is proportional to the vehicle speed.

$$K\,\frac{1+\tau s}{s} \tag{11}$$

Finally, the transfer function from the slip ratio command to the actual slip ratio becomes

$$\frac{\Delta\lambda}{\Delta\lambda^*} = \frac{1}{1 + Na\,\frac{M_w + M\,(1-\lambda)}{M\,(1-\lambda)}\,\frac{1}{K}\,s} \tag{12}$$

If λ<<1, this is a simple first order delay characteristics with a time constant which can be adjusted by K. Here, we put this response time 50～100[ms].

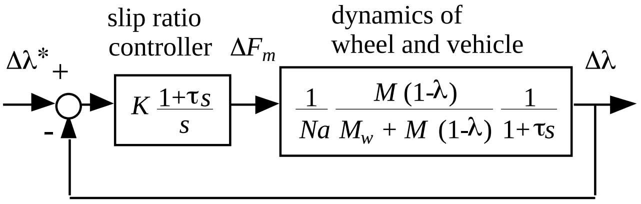


Fig.7. Slip ratio controller.

Fig.8 shows the nominal slip ratio used in the slip ratio controller. We defined it by a=1. The point of a=1 is located just in left side of the peak and is stable. Both of the longitudinal and lateral forces are kept still high.

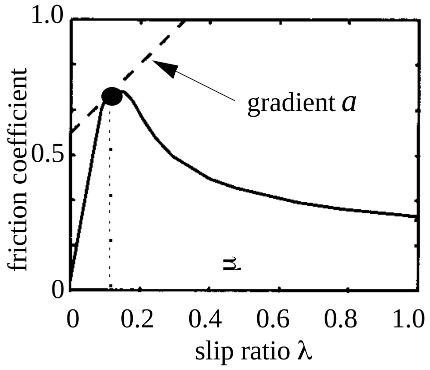


Fig.8. Nominal slip ratio is given by a=1.

C. Robustness to Parameter Variation

Because the actual system parameters change widely, we should investigate the robustness of the slip ratio controller. Fig.9 draws the root locus to the continuous change of K and a.

From the figure, we can see that the roots move to the left half plane when the controller gain K increases. It is interesting that this controller stabilizes the system even when actual a is negative, although the roots move to unstable region.

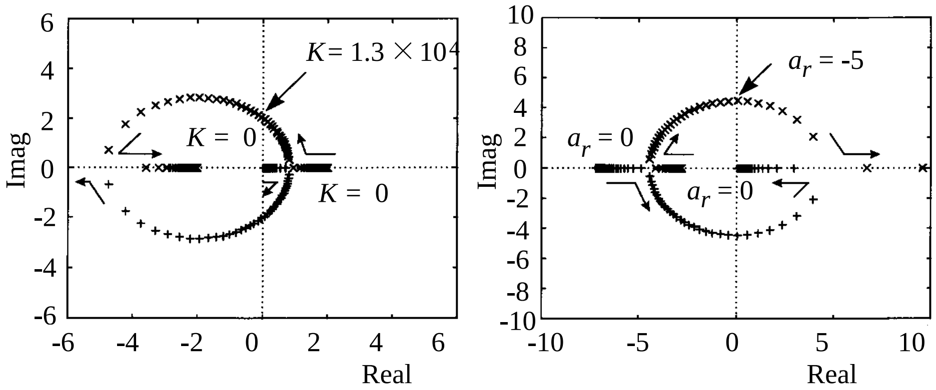


Fig.9. Root locus against parameter variation

D. Simulation of Slip Ratio Control

Fig.10 shows the vehicle model we used in the simulation. T represents the motor torque and r the total gear ratio of the drive train. F_d represents the summation of traction force transferred to the contact point of tire and road surface. It is the product of traction coefficient μ and $N=Mg$, the vertical load on the contact point. μ is defined as a function of λ (slip), which is given by the measured curve shown in Fig.11.

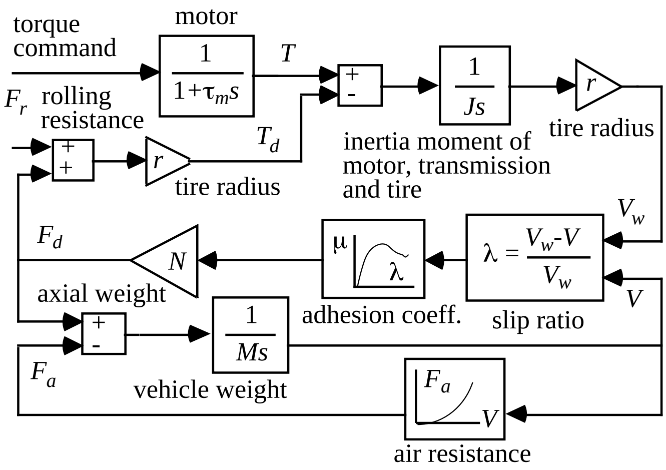
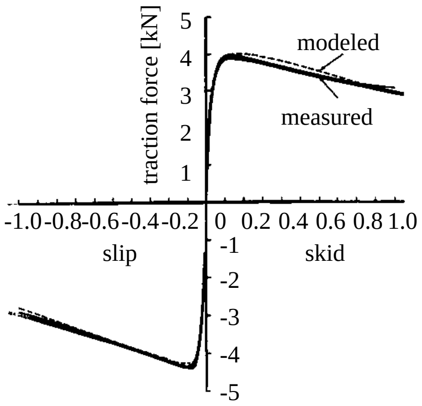


Fig.10 Vehicle model used in the simulation.



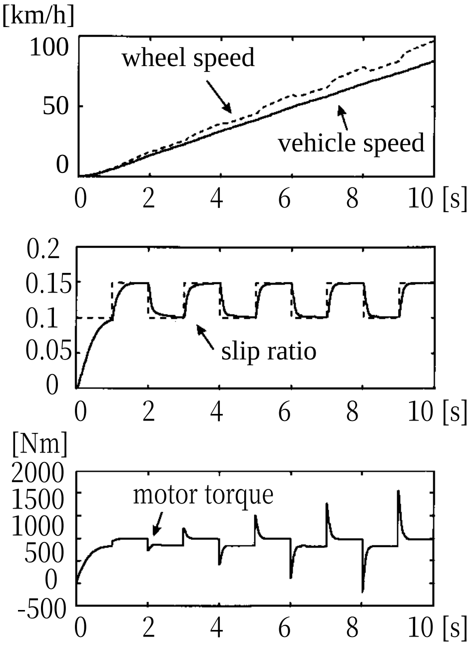


Fig.11. μ–λ characteristics used in the simulation.

Fig.12 Simulation of the slip ratio control.

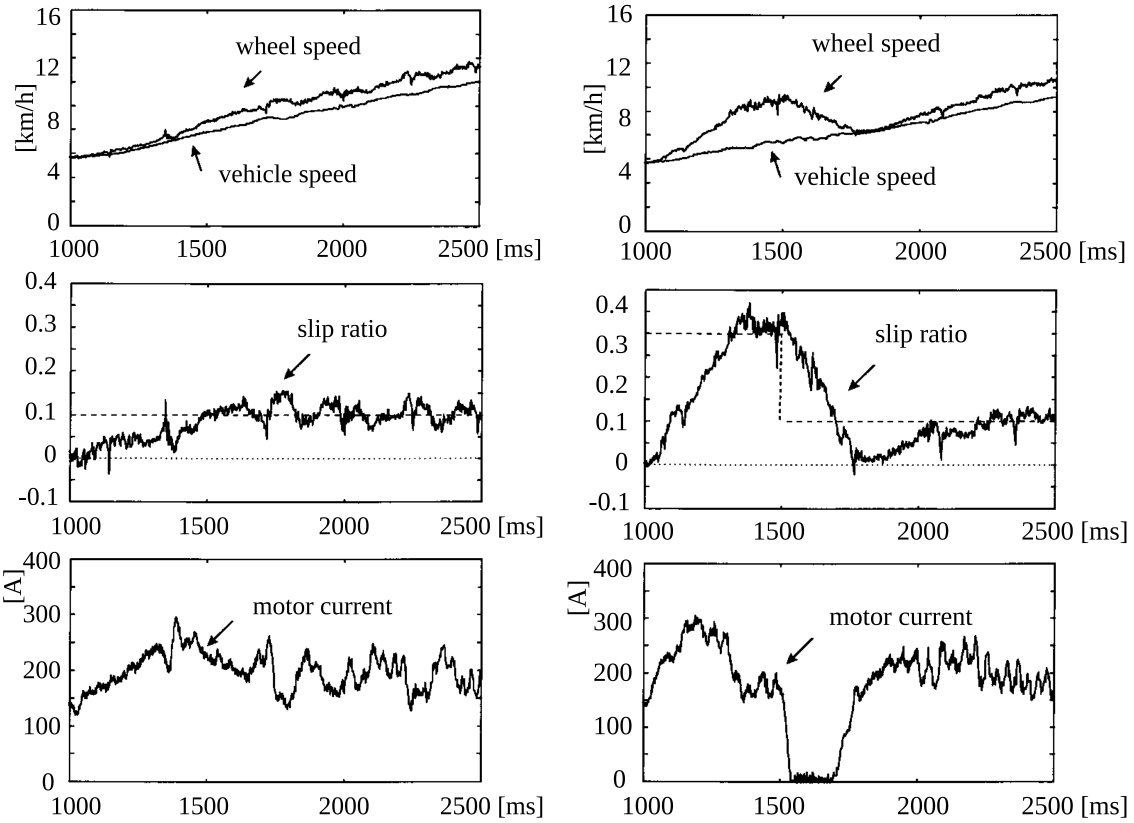
Fig.12 is the simulation result. The response time of the slip ratio controller is set to be 100[ms]. We can see good response characteristics.

E. Experimental Results of Slip Ratio Control

Fig.13 shows the experimental results of the slip ratio control using the laboratory-made experimental electric vehicle "UOT Electric March". Here the response time is 50[ms] and the target slip ratio is 0.1 in Fig.13(a) and is changed stepwise from 0.3 to 0.1 in Fig.13(b).

Basically we can see fairly good performances but there are some problems.

First, the actual value of a was much smaller than the nominal value: 1. This made the response time longer than the designed value. Next, in Fig.13(b), we see an undershoot to the slip ratio command of 0.1. This is because the motor controller we used is just an 1-quadrant chopper, who can not absorb the motor current.



(a) constant slip ratio command (b) changing slip ratio command

Fig.13. Experimental results of the slip ratio control

VI. ESTIMATION OF ROAD CONDITION

In the previous chapter, we showed effective slip ratio control. Next problem is how to give the optimal slip ratio to the slip ratio controller.

We showed the relation between the slip ratio λ and the friction coefficient μ in Figs.1 and 11, but it varies very widely according to road surface condition as shown in Fig.14. It is clear that the slip ratio where the friction force takes its maximum value vary according to road condition. This means that road condition should be estimated relatively quickly for commanding the optimal slip ration to the slip ratio control.

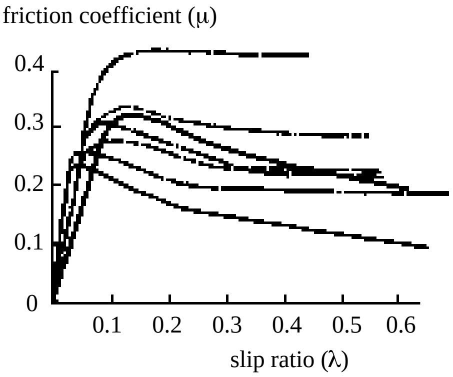


Fig.14. Various Road Condition. (Actual explanation of each curves is omitted.)

To know the road surface condition, we should estimate the friction coefficient. If we can measure the vehicle speed directly by using non-driven wheel, the friction coefficient μ can be obtained by eq.(13) based on eqs.(3) and (4).

$$\mu = \frac{M}{N}\frac{dV}{dt} \tag{13}$$

When the vehicle speed can not be measured directly, we can estimate μ based on eq.(14).

$$\mu = \frac{1}{N}\left(F_m - M_w\frac{dV_w}{dt}\right) \tag{14}$$

In our case, we can use both of these two methods. Fig.15 shows the estimation result of μ-λ curve of dry asphalt road when no slip control is active. At the point around λ=0.08, the gradient *a* of μ-λ curve is about 1.

Fig.16 shows the estimation results on wet iron surface under the slip ratio control proposed in the previous chapter. Here, the optimal slip ratio is smaller than 0.05. It is also noticed that, in our experiment shown in Fig.13(a), the actual gradient of μ-λ curve at λ=0.1 was almost -1. We can see that the slip ratio controller is effective even when the operation point is unstable, but, in this case, we should have commanded a lower slip ratio.

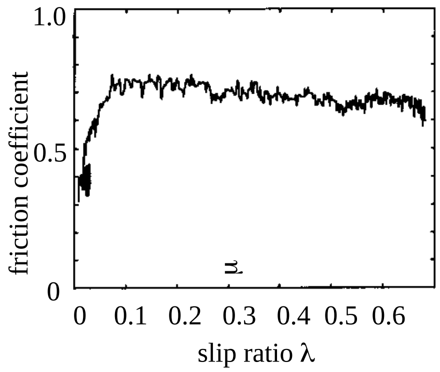


Fig.15. Estimation result of μ-λ curve of dry asphalt road.

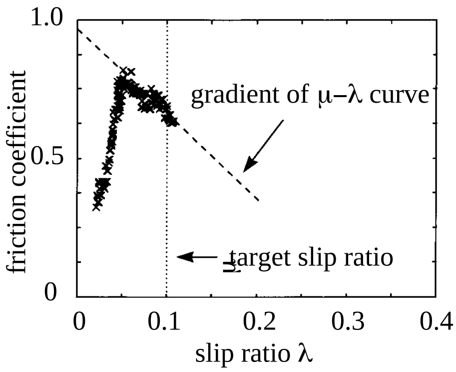


Fig.16. Estimation result of μ-λ curve of wet iron plate under the slip ratio control

VII. CONCLUSION

We are now proposing a new field of "Motion Control of Electric Vehicle". EV is a very interesting object combining electrical and mechanical engineering fields from the view point of motion control. As an example, we proposed advanced adhesion control utilizing quick and precise torque response of electric motor.

We proposed the Model Following Control and the Optimal Slip Ratio Control. We confirmed that MFC can reduce its torque quickly when the motor speed is suddenly increased by tire slip. Next, we showed that the optimal slip ratio control has more advanced performance. Such kinds of quick controls are firstly realized only in electric vehicles. It is clearly shown that relatively precise control theory can work well in actual experiments.

Advanced adhesion control is helpful for lateral control like yaw disturbance attenuation. This is because the proposed optimal slip ratio control keeps the tire slip within the small region where both of the longitudinal and lateral adhesion coefficients are still high enough.

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APPENDIX

Configuration of UOT Electric March

We developed a real test electric vehicle "UOT Electric March (Todai Sangatsu Go)" seen in Fig.A-1. It is a so-called convert car, whose IC engine is replaced by an electric motor.

The front two wheels are driven by a 19[kW] series-wound DC motor through a 5 speed manual transmission and a differential gear. The 1-quadrant DC chopper supplies power to the motor. Its current limit is 400[A] and can produce maximum torque over 100[Nm], which is enough to perform the slip experiment. Current and speed sensors are also implemented. To detect the vehicle speed, a speed sensor is implemented in the rear wheel.

TABLE A-I SPECIFICATION OF UOT ELECTRIC MARCH

Conversion Base	Nissan March (Micra)
size	3785×1560×1395[mm]
weight	900[kg](batteries included)
Motor	Advanced D.C. Motors, Inc.
type	DC series wound
rated power (@120V)	19[kW](1hr.), 32[kW](5min.)
size/weight	ϕ 232, length 397[mm], 65[kg]
Controller	Curtis Instruments, Inc.
type	MOSFET PWM Chopper
operating frequency	15[kHz]
rated voltage/current	120[V]/400[A]
Battery	Japan Storage Battery Co.,Ltd. GTX-130E41L
type	lead acid
voltage/capacity	72[V]/92[Ah](5hr)
weight	27.5[kg]×6
CPU	PC9801NS/T (386SL, 20MHz)
weight	3.2[kg]
A/D and D/A converters	12bit, 8ch / 12bit, 2ch

Fig.A-2 shows the control system of the vehicle and TABLE A-I gives its specification. We use a note-type personal computer to realize the torque control. It not only executes the control algorithm and puts out the voltage command to the chopper, but also reads, shows and records the sensor data. As the control algorithm is written by software (C-language), we can easily investigate various control strategies.

Fig.A-3 shows the new electric vehicle we are making now. It has four wheel-in motors in each wheel. Using this vehicle, we are planning to perform advanced experiments on vehicle dynamics control.

DC motor

Fig.A-1 UOT Electric March and its Traction Motor.

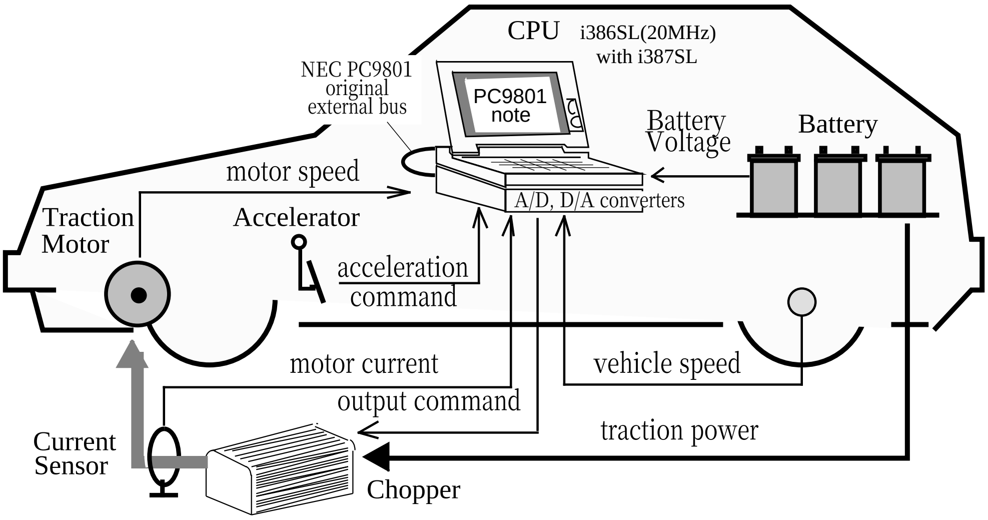

Fig.A-2 Configuration of UOT Electric March.

PM In-wheel Motor * 4

Fig.A-3 UOT Electric March II and its Traction Motor.

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