Experimental Studies on Vehicle Motion Stabilization with 4 Wheel Motored EV

Shin-ichiro Sakai, Takahiro Okano, Tai Chien Hwa, Toshiyuki Uchida, Yoichi Hori

Abstract

EV has great advantages on control performance: fast and accurate motor torque generation. This paper points out these advantages clearly with our experimental studies. These studies can be classified into three categories: 1) fast feedback approach for wheel skid prevention or hybrid ABS, 2) lateral stability enhancement with four motors and minor feedback loops, and 3) road condition estimation with accurate motor torque value. Some experimental evaluations are carried out with novel "UOT Electric March II". This four wheel motored EV is also introduced.

keywords: traction control, control system, braking, safety, regenerative braking.

1 Introduction

Recently, electric vehicles (EVs) are intensively developed. With improvement of motors and batteries, some pure EVs (PEVs) with only secondary batteries have already achieved enough performance. Hybrid EVs (HEVs), like Toyota Prius, are going up to the commercial products. Fuel cell EVs (FCEVs) will possibly be major vehicles in this 21^{st} century. The background of this developments is energy and environmental problems, thus main concern over EVs is energy efficiency and environmental impacts. However, another important advantage exists, which is not recognized well yet. It is controllability of electric motors.

From the viewpoint of electrical and control engineering, EVs have evident advantages over internal combustion engine vehicles (ICVs). These advantages can be summarized as:

1. ***Torque generation of electric motor is very quick and accurate, for both accelerating and decelerating.***

   This should be the essential advantage. ABS (antilock brake system) and TCS (traction control system) should be integrated into "total TCS", since a motor can both accelerate or decelerate the wheel. Its performance should be advanced one, if we can fully utilize the fast torque response of motor [1].

2. ***Motor can be attached to each wheel.***

   With small motors like in-wheel motors [2], even the anti-directional torque generation is possible on left and right wheels. In automobile engineering, such approach is known as DYC (direct yaw moment control) [3] [4]. Distributed motor will possibly enhance its performance.

3. ***Motor torque is easily comprehensible.***

   There exists little uncertainty in driving or braking torque inputted by motor, compared to that of combustion engine or hydraulic brake. Therefore, simple "driving force observer" can achieve a real-time observation of driving/braking force between the tire and road surface [5] [6]. This second advantage will contribute a great deal to several applications like road condition estimation.

Definitely, these indicate the novel approach for vehicle motion control in EVs. Automobile engineers recently agree that active vehicle control is the important technique. It is directly connected with safety, or human life. We, electric engineers, will be able to contribute a lot to this novel and important theme: advanced motion control of EVs.

In this paper, several studies are introduced in three categories: longitudinal control, lateral control and parameter estimation. Feedback based approach with fast motor response is our basic strategies for wheel control or longitudinal control. Such minor controller can change the plant dynamics and enhance the stability on slippery road surface. Section 3 describes the basic theory and experimental results of wheel skid prevention. One of the application of this approach is "Hybrid ABS". "Hybrid ABS" is the cooperative ABS system using both hydraulic and regenerative torque. Hydraulic torque is applied for low-frequency bias torque component, and regenerative torque generates high frequency component. It is also introduced in Section 3.

Section 4 concerns the enhancement of lateral motion stability on the basis of section 3. For vehicle with two or four motors, feedback controller proposed in section 3 can be applied for every driving wheel independently. If each wheel's dynamics is improved with this minor loop, the lateral dynamics is expected to be stabilized. This idea is studied with both simulations and experiments in section 4.

Section 5 describes the estimation or observation with accurate motor torque value. Parameter or status estimation is another important issues in vehicle control issues. Proposed "road condition estimator" judges if the current road is "slippery" or not. The other example is wheel skid detector, which detects the wheel skid without chassis velocity information. These methods depend on the accurate motor torque value, which is another advantage of EVs.

"UOT Electric March II" is our novel experimental EV. It is "4 wheel motored EV": every wheel has its own driving motor. This EV is projected and designed for intensive motion control studies, thus computers for motion control, sensors like fiber-gyro type yaw rate sensor are equipped. Section 2 introduces this EV, before the academic discussions.

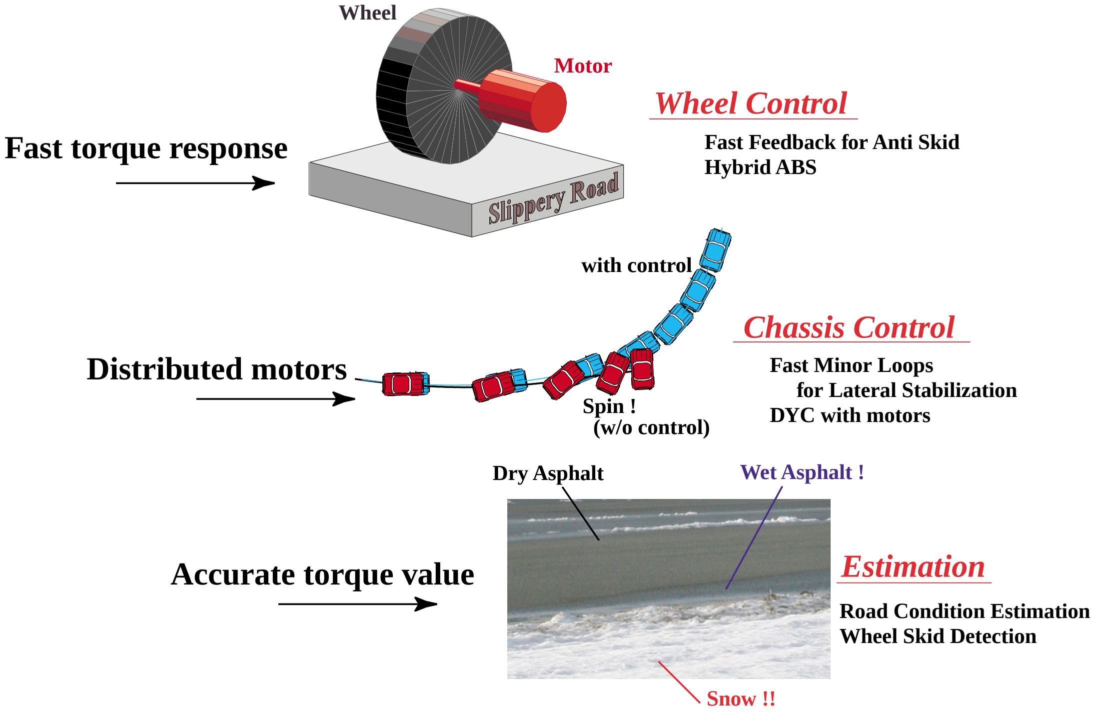

Fig. 1: EV's three essential advantages in motion control issues.

2 "UOT Electric March II", novel four wheel motored EV

For vehicle control studies, experimental evaluation is quite important. In 1997, we constructed "UOT Electric March I", which is our first EV for experiments. This vehicle was very simple: driven with only one DC motor, and no regenerative braking system. Still it was useful, however, for longitudinal experiments. Several basic studies were carried out with this EV [1].

"UOT Electric March II" is our novel EV completed in 2001. This EV can be characterized by its original motor configuration: 4 independent driving motors. Each wheel has their own driving motor, therefore, driven wheels can be independently controlled. Regenerative braking is also available in this vehicle. We ourselves designed and built up this vehicle, based on the conventional ICV "Nissan March".

The specification of this EV focuses on the motion control experiments. It has adequate devices for experiments: on-board PCs and several sensors like fiber-optic gyro. Motion controller constructed in the PC outputs the torque commands, and inverter units generate the torques of these values. This precise torque generation is achieved by motor current controller in the inverter unit. On the other hand, other specs like distance for one-charge, energy efficiency, or driving comfort are excluded from targets. Table 2 summarizes the key specifications of "UOT Electric March II".

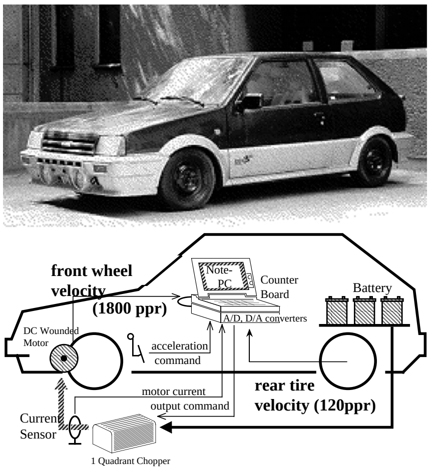

Fig. 2: "UOT Electric March-I".

Motor	**DC Motor**
5 min.	32.5[kW] (44.3[HP])
Max. Torque	85[Nm]
Gear Ratio	13.5
Battery	**Lead Acid**
Nominal Capacity	92[Ah]
Total Volt.	120[V] (with 10 units)
Chassis	**Nissan March**
Weight	1000[kg]
Wheel Inertia	21.1[kgm^2]*
Wheel Radius	0.26[m]
CPU	i386, 20[MHz]
Encoder(front/rear wheel)	1800 / 120[ppr]

* ... Including the rotor of motor, affected by gear ratio.

Table 1: Specifications of "UOT Electric March I".

Drivetrain	**4 PM Motors**
Max. Power(20 sec.)	36 [kW] (48.3[HP])*
Max. Torque	77* [Nm]
Gear Ratio	5.0
Battery	**Lead Acid**
Weight	14.0 [kg](for 1 unit)
Total Voltage	228 [V] (with 19 units)
Base Chassis	**Nissan March K11**
Wheel Base	2360 [m]
Wheel Tread F/R	1365/1325 [m]
Total Weight	1400 [kg]
Wheel Inertia**	8.2 [kg]***
Wheel Radius	0.28 [m]
Controller	
CPU	MMX Pentium 233[MHz]
Rotary Encoder	3600 [ppr]***
Gyro Sensor	Fiber Optical Type

* ... for only one motor.
** ... mass equivalent.
*** ... affected by gear ratio.

Table 2: Spec of "UOT Electric March II".

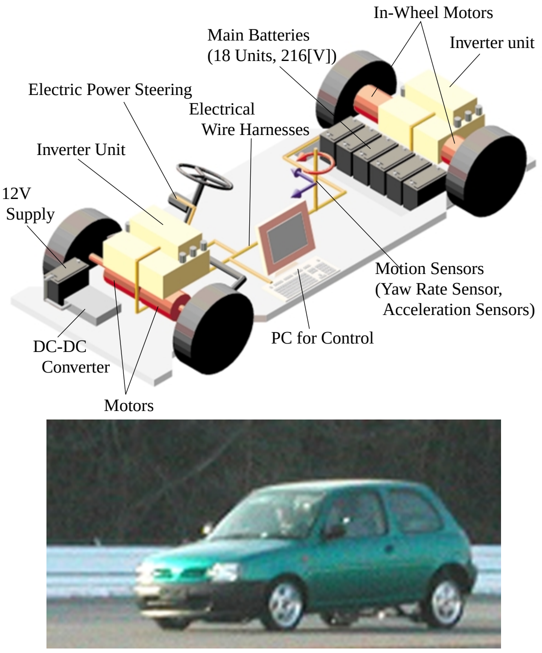

Fig. 3: "UOT Electric March II" running at about 100 [km/h].

3 Wheel Control for Skid Prevention with Fast Feedback

In this section, the wheel velocity controller for skid prevention is discussed. The starting point of this idea is to utilize the knowledge on motion control, which is based on the motor control. In general, the feedback controller can change the dynamics of plant, or we can re-design the plant dynamics. For example, the plant can be insensitive against disturbance if appropriate feedback controller is applied. Such feedback controller requires fast response of actuator, and it is available in EVs. So, how we should design the controller or plant dynamics for skid prevention? This is the main topics in this section.

3.1 Basic Slip phenomena and linear slip model

Ordinary, slip ratio λ is used to evaluate the "slip". Slip ratio λ is defined as,

$$\lambda = \begin{cases} \dfrac{V_w - V}{V_w} & \text{: for accelerating wheel,} \\ \dfrac{V_w - V}{V} & \text{: for decelerating wheel,} \end{cases} \tag{1}$$

where V is the vehicle chassis velocity. V_w is the velocity equivalent value of wheel velocity, $V_w = r\omega$, where r, ω are the wheel radius and wheel rotating velocity, respectively.

With simple one wheel model (Fig. 4), the motion equations of wheel and chassis can be obtained as

$$M_w \frac{dV_w}{dt} = F_m - F_d(\lambda), \tag{2}$$

$$M \frac{dV}{dt} = F_d(\lambda), \tag{3}$$

if air resistance on chassis and rotating resistance on wheel are both negligible. M and M_w are the vehicle weight and the mass equivalent value of wheel inertia, respectively. F_m is the force equivalent value of accelerating/decelerating torque, generated by engine, hydraulic brake system or motor. F_d is the driving/braking force between the wheel and the road surface. This F_d has nonlinear dependence on the slip ratio λ, such as in Fig. 5 [1].

For the controller design process, linear skid model is derived from (1)-(3) and $F_d(\lambda)$ in Fig. 5. Nonlinearity exists in $F_d(\lambda)$ or $\mu - \lambda$ curve, therefore, perturbation equation for $F_d(\lambda)$,

$$\Delta F_d = N\Delta\mu = Na\Delta\lambda \tag{4}$$

$$= -\frac{1}{V_{w0}}\Delta V + \frac{V_0}{V_{w0}^2}\Delta V_w \tag{5}$$

is used here. The parameter a is the gradient of $\mu - \lambda$ curve,

$$a = \left.\frac{\partial\mu}{\partial\lambda}\right|_{(V_0, V_{w0})}. \tag{6}$$

V_{w0}, V_0 are the wheel velocity and chassis velocity at the operational point, respectively. With (1)-(3) and (5), the transfer function from motor torque F_m to the wheel velocity V_w is

$$P(s) = \frac{\Delta V_w}{\Delta F_m} = \frac{1}{(M_w + M(1-\lambda_0))s} \frac{\tau_w s + 1}{\tau_a s + 1}, \tag{7}$$

where

$$\tau_a = \frac{M_w V_{w0}}{aN} \frac{M}{M(1-\lambda_0) + M_w}, \quad \tau_w = \frac{M V_{w0}}{aN}. \tag{8}$$

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[1] $\mu = F_d/N$, where N is the normal force on the wheel.

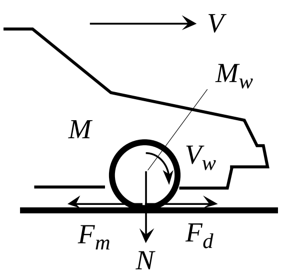

Fig. 4: One wheel model.

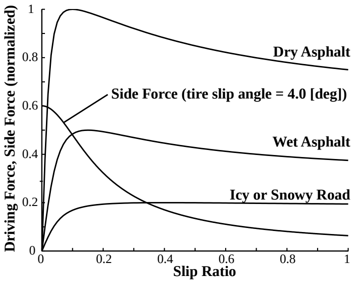

Fig. 5: Typical $\mu - \lambda$ curve.

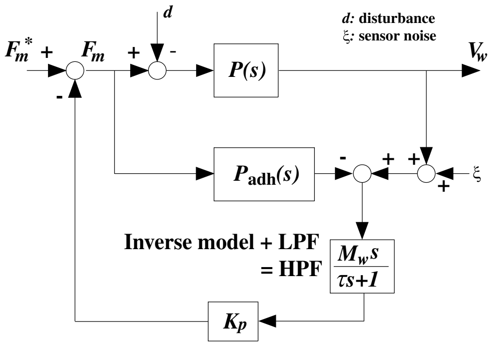

Fig. 6: Proposed feedback controller.

λ_0 is a slip ratio at the same operational point (V_0, V_{w0}).

From (7)-(8), the most simple models $P_{\text{adh}}(s)$ (for adhesive wheel) and $P_{\text{skid}}(s)$ (for completely skidding wheel) are

$$P_{\text{adh}}(s) = \frac{1}{M + M_w}\frac{1}{s}, \qquad P_{\text{skid}}(s) = \frac{1}{M_w}\frac{1}{s}. \tag{9}$$

3.2 Controller design for anti-skid

Therefore, One dominant phenomenon in the wheel skidding is the rapid change of wheel rotating velocity. With wheel skidding during the acceleration, the wheel velocity rapidly increases, and during the deceleration it rapidly drops due to the wheel lock. Eq. (9) describe that sudden drop of wheel equivalent inertia causes this rapid change of wheel velocity. Based on this viewpoint, we design the feedback controller of Fig. 6 [1]. This controller can suppress such sudden drop of inertia as shown in Fig. 7.

Fig. 7 is the bode diagram of V_w/F_m^*. Left graph plots V_w/F_m^* for wheel without controller, i.e., plots $P_{\text{adh}}(s)$ and $P_{\text{skid}}(s)$. If the controller of Fig. 6 is applied, these transfer functions are changed into the ones in the right graph. These figures clearly indicate that the dynamics of skidding wheel comes to be almost same as that of adhesive wheel, the "heavy" wheel. The wheel with proposed controller is insensitive for slip phenomena.

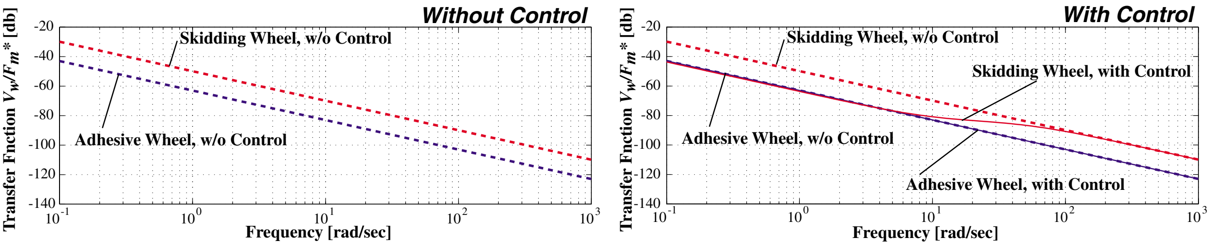

Fig. 7: Bode diagram of V_w/F_m^*. $K_p = K_p{}^* = \frac{M+M_w}{M_w}$. $\tau = 0.1[sec]$.

3.3 Experimental results of wheel velocity feedback

Experiments were carried out to confirm the proposed method. These experiments were carried out with "UOT Electric March-I", which is our another laboratory-made EV (Fig. 2) constructed in 1997 [1]. To examine the effect of wheel velocity control for skid avoidance, slippery low μ

road is required. We put the aluminum plates of 14[m] length on the asphalt, and spread water on these plates. The peak μ of this test road is about 0.5. This value was estimated based on some other experimental results [6].

Fig. 8 shows the time responses of slip ratio. In these experiments, vehicle accelerated on the slippery test road, with lineally increasing motor torque. Without control, the slip ratio rapidly increases. On the contrary, the increase of slip ratio is relatively slow with proposed controller. As mentioned above, the wheel equivalent inertia during the wheel skidding comes to be "heavy" with wheel velocity control, thus the rapid increase of slip ratio can be suppressed.

Note that this method cannot be a complete skid prevention controller by itself. Proposed controller suppressed the rapid growth of slip ratio, however, the slip ratio finally exceeded the stable limit (Fig. 8). Therefore, we suggest this method as a minor-loop controller, to improve other method like conventional ABS or skid detection technique with EV [7].

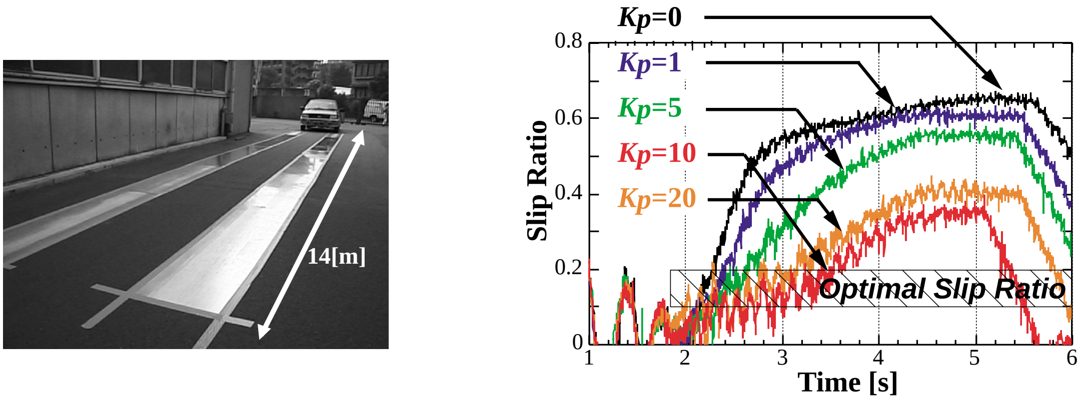

Fig. 8: Effect of wheel velocity control for skid prevention with τ=0.1[s] (Experimental results.) K_p^* is 4.52 for this vehicle.

3.4 Hybrid ABS -one application of wheel velocity feedback-

Generally speaking, HEV has only small motor for torque assist. Thus the regenerative braking must cooperate with hydraulic braking system(Fig. 9). This cooperation is designed only for the energy efficiency, not for the wheel skid prevention. We have proposed "Hybrid ABS(H-ABS)", which is the cooperative ABS with electric and hydraulic torque. The point is that, HEV's motor has relatively small but rapid torque output, and hydraulic braking system has large but slow torque generation.

Currently, two approaches are discussed. First approach is the "plug-in H-ABS". Motor controller is just added to the normal hydraulic ABS, without changing the original ABS controller (Fig. 10). Generally, the ABS controller is on-off type controller. The plug-in feedback controller prevents the rapid change of wheel velocity with feedback, accordingly compensates the high frequency dynamics of original ABS.

The applied feedback controller in Fig. 10 is very similar to the one in section 3. This controller prevents the sudden change of wheel inertia or wheel velocity, thus the wheel velocity oscillation can be suppressed. Simulation results (Fig 11) shows this effect typically. Accordingly, the braking distance can be shorten. However, this is just the simple simulation results and farther experimental studies should be carried out.

This "plug-in" type's advantages are, (a) easy to apply and (b) only concerning with wheel velocity, and not using chassis velocity for feedback signals. Another approach is, of course, to design both regenerative and hydraulic braking controller. Controller design with frequency-division seems to be effective with our basic simulations. Experimental study of this method is also planed with "UOT Electric March-II".

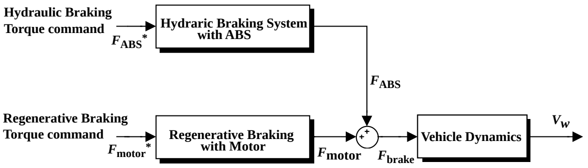

Fig. 9: Conventional regenerative braking. ABS actuator is only hydraulic one.

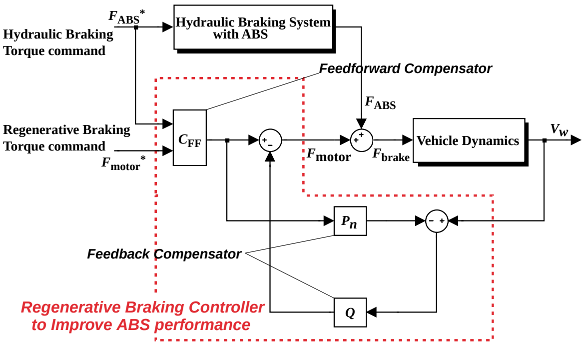

Fig. 10: "H-ABS", cooperative ABS with both electric and hydraulic torque.

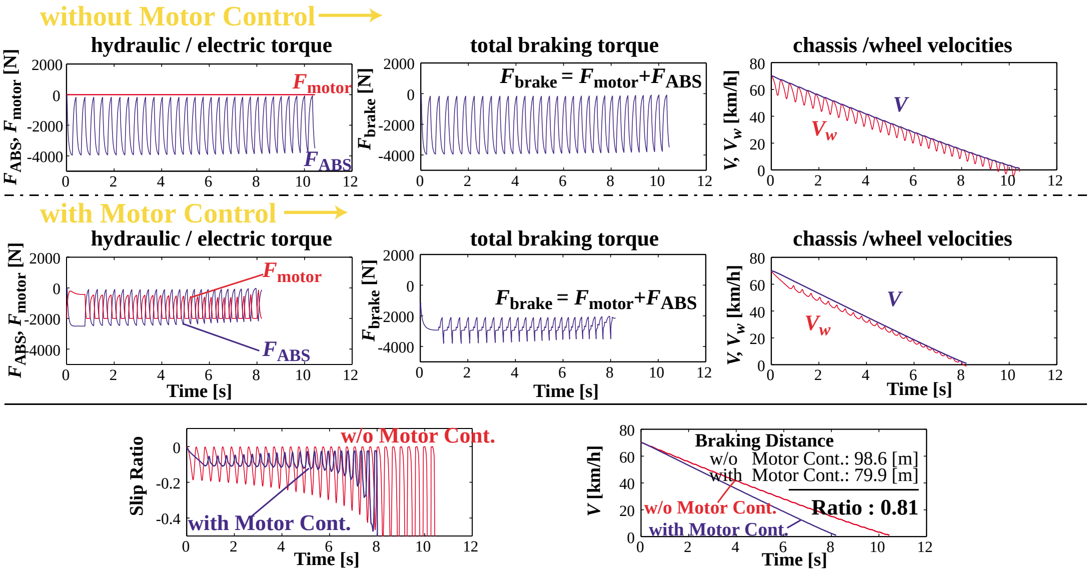

Fig. 11: Effect of plug-in H-ABS. Upper row shows the data of simulated conventional ABS. Simple on-off ABS logic causes oscillation. Applied controller with electric motor can suppress this oscillation with compensating the high frequency dynamics(middle row). Consequently, slip ratio oscillation is relatively small and braking distance is shorten(lower row) with proposed methods.

4 Lateral Motion Stabilization with Motor Control

4.1 Concept and Simulation Studies

In the previous section, wheel velocity feedback method was discussed. With this method, wheel equivalently has heavy inertia during slip. This suppresses the rapid increase of slip ratio. Then, what will happen if we apply such feedback loop for every wheel of turning vehicle on slippery road ?

As commonly known, the vehicle lateral motion can be sometimes unstable. This instability occurs in such situation as rapid braking during the turning, especially with slippery road condition with snowy or rainy weather. Here we assume that one small motor is attached on every wheel of target EV. In-wheel motor is a typical example. With such motors, the wheel velocities can be controlled independently. Our simulation results (Fig. 12) show that this minor loops can enhance the vehicle's lateral stability [8]. Chassis's 3-DOF nonlinear motion, four wheel's rotation and dynamic load distribution are calculated in these simulations.

In these simulations, the vehicle starts running on the slippery road ($\mu_{\text{peak}} = 0.5$), turning left with steering angle $\delta_f = 3$ [deg]. Then at 5.0 [sec], the driver inputs rapid braking torque $F_m = -1100$[N] on each wheel. This torque exceeds the tire performance. Therefore, the wheel skid occurs and the chassis starts the spin motion, although the driver stops braking at 9.0 [s]. This wheel skidding is serious at rear-left wheel especially, since the center-of-gravity is shifted and the load distribution varied.

On the contrary, if the wheel velocity controller is applied independently for each wheel, such dangerous spin motion is prevented. The rear-left wheel's torque is most reduced automatically. Note that this method uses only wheel velocities as feedback signals, therefore, differs considerably from conventional methods like DYC [3] [9]. The autonomous stabilization of each wheel, which is achieved with wheel velocity feedback, enhances the stability of vehicle lateral motion on slippery road. This effect is demonstrated in the next subsection.

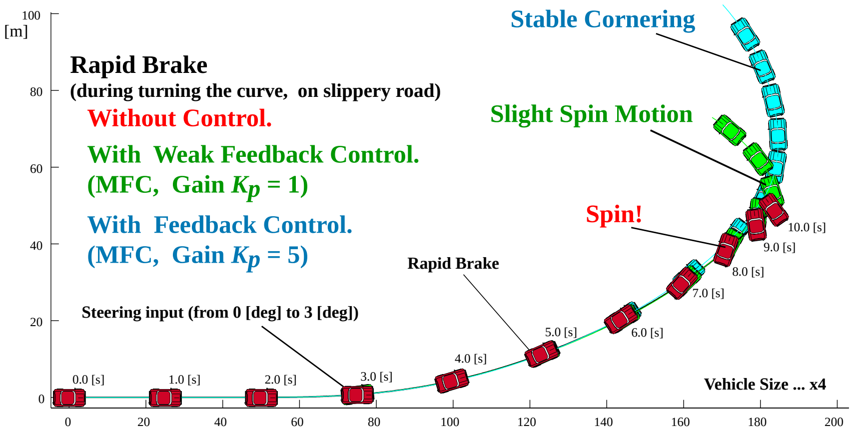

Fig. 12: Stabilizing effect with "controlled four wheels" is visualized with vehicle's trajectory [8].

4.2 Basic Experimental Results with "UOT Electric March II"

Then the results of first experiments using "UOT Electric March II" is introduced here. In these experiments, "UOT Electric March II" was turning on the slippery test road, so-called skid pad (Fig. 13). At first, it was making steady turning in the clockwise direction. Turning radius and chassis velocity were about 25-30 [m] and 40[km/h], respectively. These values were closed to the unstable region. At 0 [s], acceleration torque of 1000 [N] was applied for rear two motors. Without any feedback control, this excessive acceleration causes the unstable vehicle motion. Fig. 14 shows this unstable vehicle motion [2]. The rear-right or rear-inside wheel started skidding seriously. Then yaw rate γ unstably grew as shown in the upper-right graph of Fig. 14. It indicates the spin motion. Vehicle was completely out of control and at 2[sec], experiment was terminated for safety reasons.

On the contrary, such dangerous motion could be prevented with minor feedback of wheel velocity. Fig. 15 and Fig. 16 shows this effect clearly. Note that controllers on rear-left and rear-right wheels are the same and independent ones. Each controller only requires the value of each wheel's velocity, thus it is not "connected" with each other in any meanings. Consequently, it can be said that autonomous stabilization of each driven wheel was achieved, and it enhanced the vehicle lateral stability. This indicates the validity of simulations in the previous section.

One of the remaining problems is the high-frequency oscillation induced at the rear wheels. We suppose that it depends on the design of controller. The cut-off frequency τ in the proposed controller (Fig. 6) may have the important influence on this oscillation, however, such discussions must wait for the next experiments.

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[2] Chassis velocities in Figs. 14 and 15 are the mean values of trailing front wheels.

Fig. 13: Photo of turning experiments with 4W-motored EV “UOT Electric March II” (Fig. 14-15).

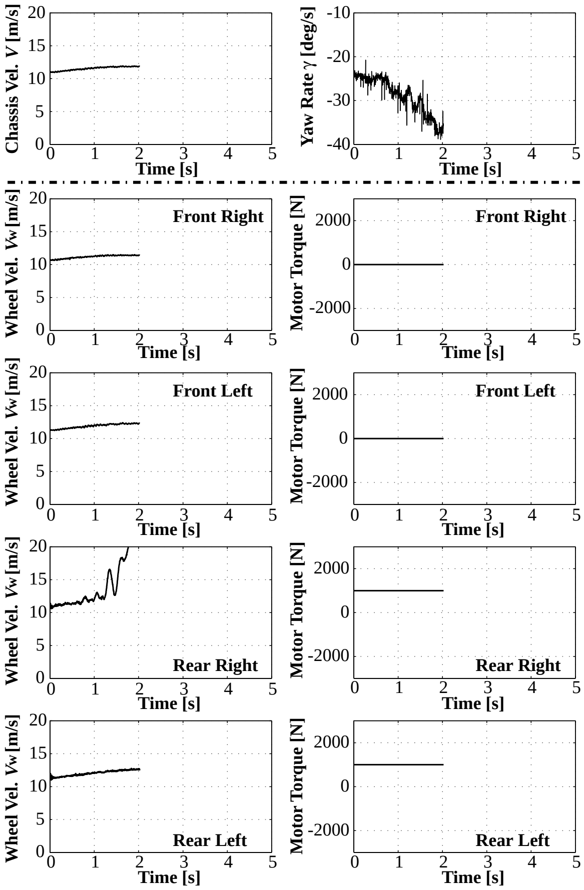

Fig. 14: Unstable turning with sudden acceleration torque on rear wheels. Vehicle made steady turning before torque inputs.

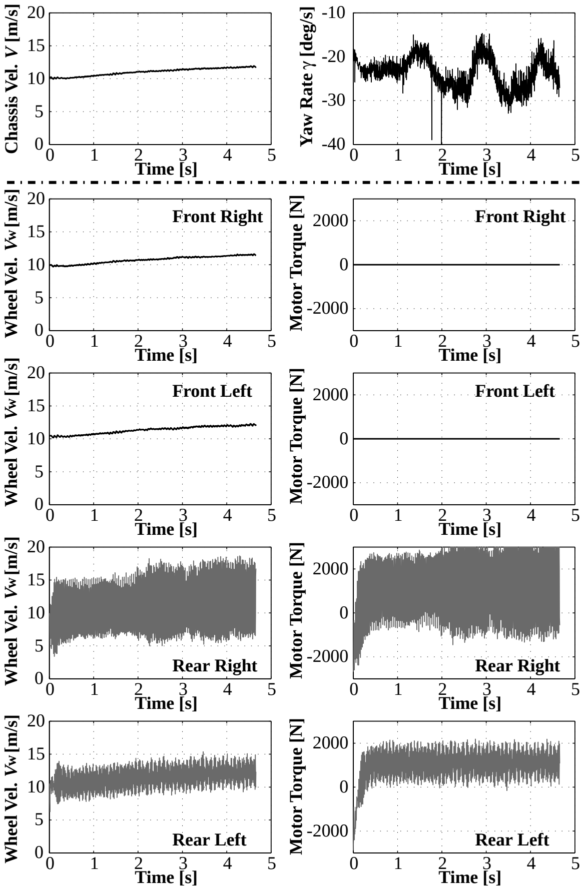

Fig. 15: Stabilizing effect of wheel velocity feedback. Proposed controller of Fig. 6 was applied on both rear wheels.

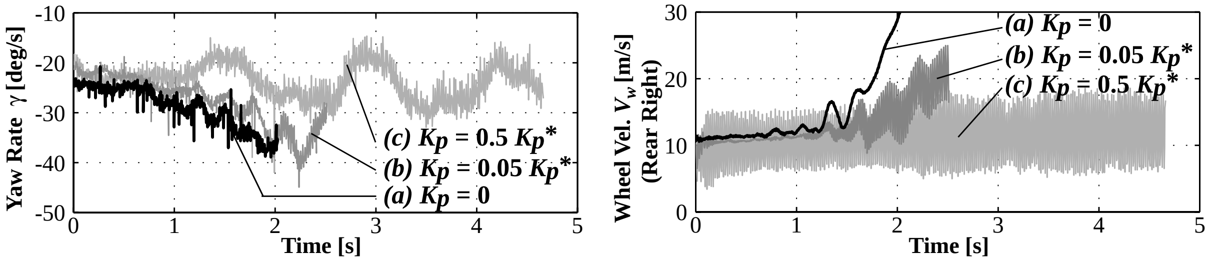

Fig. 16: Comparison of vehicle motion: (a) without feedback controller, (b) with weak feedback controller, (c) and adequate feedback controller. K_p^* is 45.2 for this vehicle. τ in the controller was 0.1 [s].

5 Observation and Estimation: application of accurate motor torque value

Motor torque generation is quite precise, thus accurate value of motor torque can be utilized. It can be a great advantage for parameter estimation issues. Estimation or observation issues are also important as control topics, since some important values like slip ratio, chassis slip angle or road peak μ cannot be measured with practical sensors. These values should be estimated, if necessary. This estimation can be highly effective by using accurate motor torque value. In this section, two examples of such applications are introduced.

5.1 Road Condition Estimation [5]

The road surface condition is quite useful information for the motion controller. This information will enhance the performance of ABS or DYC, therefore, the road condition estimation is intensively studied for conventional vehicles [10]. The accurate value of wheel input torque will contribute a great deal to the the practical and precise estimation. It is available with EV or electric motor, but no so easy with ICV or combustion engine. We have proposed advanced road condition estimator for EV, which estimates the μ_{peak} value or maximum friction force during adhesive driving [5]. Fig. 17 shows the typical experimental results with "UOT March-I". This EV first ran on the dry asphalt road, then reached the wet iron plate. The road condition estimator calculated the maximum friction force between tire and road surface. This value indicates the the sudden change of road condition, as shown in Fig. 17. Note that even if the actual driving force is always less than maximum friction force, this method can estimate maximum friction force [11].

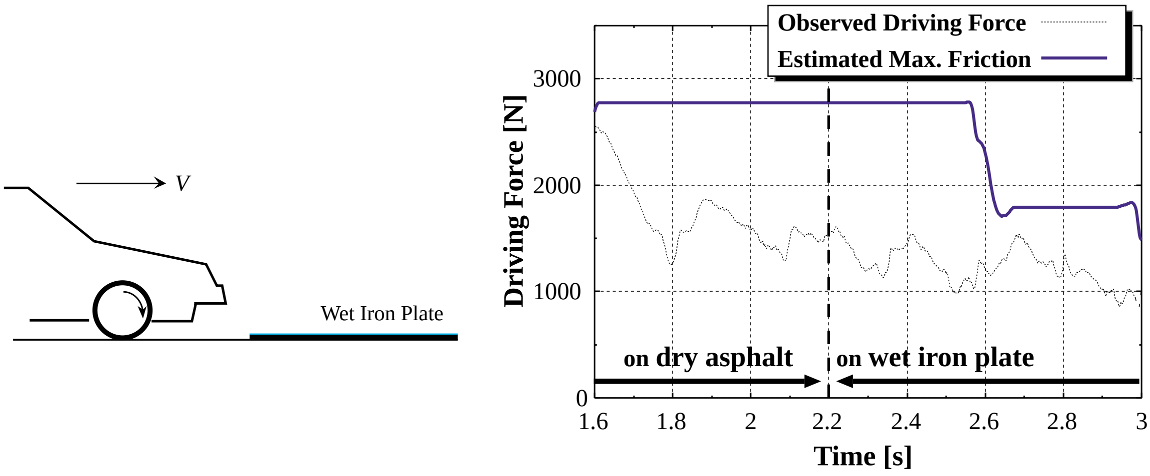

Fig. 17: Experimental results of road condition estimator. The sudden road change (left fig.) was sensed with estimated maximum friction force (right fig.)

5.2 Wheel Skid Detection [12]

Wheel skid detection is another application of accurate torque value. This method can detect the wheel skid without chassis speed reference. With accurate value of motor torque F_m, "driving force observer" can estimate the driving force F_d, which is the friction force between the road and tire. The skid detection algorithm is quite simple, basically. When F_m increases and F_d also increases, then tire should be adhesive. When F_m increases but F_d decreases, then it should be skidding. Fig. 18 is the experimental results with "UOT March I", which shows the validity of this method.

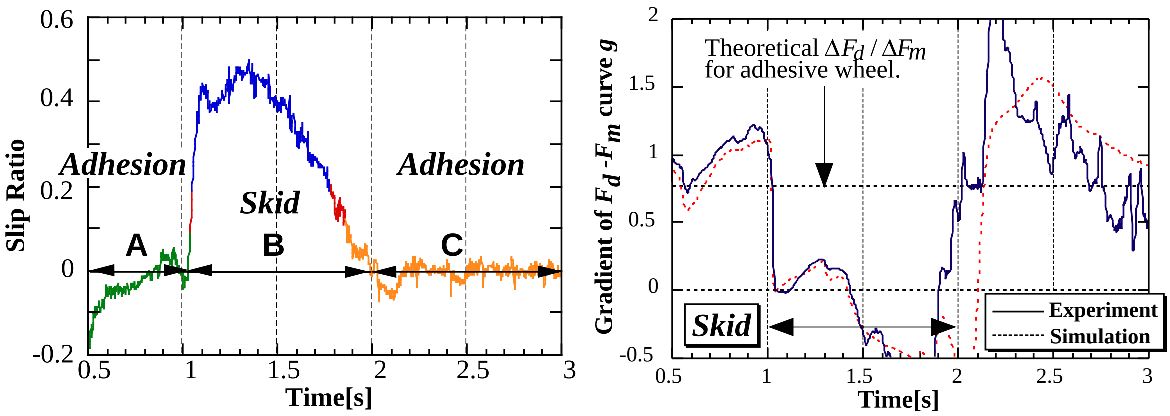

Fig. 18: Experimental results of wheel skid detector. Reference slip ratio indicates the serious skid occurred during 1-2[s](left fig.), and proposed method detected it (right fig.)

6 Conclusion

EVs' great advantages in motion control were pointed out. These can be classified into three categories: 1) fast feedback approach for wheel skid prevention or hybrid ABS, 2) lateral stability enhancement with four motors and minor feedback loops, and 3) road condition estimation with accurate motor torque value. This paper summarize our studies for these 4-5 years. The details of each research were sometimes omitted here, thus please refer our individual papers listed below with references. If such approaches make future EVs safer than ICV, then EVs will have great market value. This is what we are dreaming for the progress of EV world.

One of the remaining major interests is the relation between each wheel's dynamics and chassis lateral dynamics. This paper showed the basic results, however, intensive studies should be carried out. Theoretical analysis should be studied, especially. Final target is the collaboration of "minor wheel controller" and "total chassis controller", as depicted in Fig. 19.

This paper also introduced our novel experimental EV, "UOT Electric March II". This 4 wheel motored EV was just completed in the spring of 2001, and will play an important roll in the coming motion control studies. Farther information is at: *www.hori.t.u-tokyo.ac.jp/997/sakai.*

Again the point is the electric motor's advantage: quick and accurate torque generation and distributed torques. Currently main concerning around EV is energy efficiency. In the near future, control issues will be another major topics. We will continue our effort toward that day.

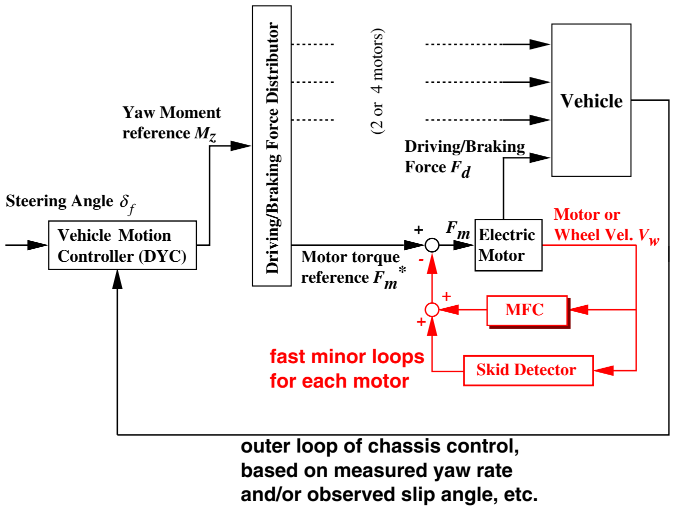

Fig. 19: Our basic idea: total system with minor feedback loops

References

[1] Y. Hori, Y. Toyoda, and Y. Tsuruoka. Traction control of electric vehicle: Basic experimental results using the test EV "UOT Electric March". *IEEE Trans. Ind. Applicat.*, Vol. 34, No. 5, pp. 1131–1138, 1998.

[2] D. Johnston. TM4 motor-wheel drive and control system: Performance, benefits and advantages.

[3] Yasuji Shibahata, et al. The improvement of vehicle maneuverability by direct yaw moment control. In *Proc. AVEC '92*, No. 923081, 1992.

[4] Sumio Motoyama, et al. Effect of traction force distribution control on vehicle dynamics. In *Proc. AVEC '92*, No. 923080, 1992.

[5] Hideo Sado, Shin-ichiro Sakai, and Yoichi Hori. Road condition estimation for traction control in electric vehicle. In *The 1999 IEEE International Symposium on Industrial Electronics*, pp. 973–978, Bled, Slovenia, 1999.

[6] Shin-ichiro Sakai, Hideo Sado, and Yoichi. Hori. Novel skid avoidance method without vehicle chassis speed for electric vehicle. In *Proc. International Power Electronics Conference (IPEC)*, Vol. 4, pp. 1979–1984, Tokyo, Japan, 2000.

[7] Shin-ichiro Sakai, Hideo Sado, and Yoichi Hori. Motion control in an electric vehicle with 4 independently driven in-wheel motors. *IEEE Trans. on Mechatronics*, Vol. 4, No. 1, pp. 9–16, 1999.

[8] Shin-ichiro Sakai and Yoichi. Hori. Advanced vehicle motion control of electric vehicle based on the fast motor torque response. In *Proc. 5th International Symposium on Advanced Vehicle Control (AVEC)*, pp. 729–736, Michigan, USA, 2000.

[9] Y. Furukawa and M. Abe. Direct yaw moment control with estimating side-slip angle by using on-board-tire-model. In *Proc. 4th International Symposium on Advanced Vehicle Control*, pp. 431–436, Nagoya, 1998.

[10] Fredrik Gustafsson. Slip-based tire-road friction estimation. *Automatica*, Vol. 33, No. 6, pp. 1087–1099, 1997.

[11] Shunichi Yamazaki, Tadashi Suzuki, and Izumi Yamaguchi. An estimation method of hydroplaning phenomena of tire during traveling on wet road. In *Proc. JSAE Spring Conference*, No. 9932421, pp. 5–8, Yokohama, Japan, 1999.

[12] Shin-ichiro Sakai, Hideo Sado, and Yoichi Hori. Novel skid detection method without vehicle chassis speed for electric vehicle. *JSAE Review*, Vol. 21, No. 4, pp. 503–510, 2000.

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