Lateral motion stabilization of 4 wheel-motored EV based on wheel skid prevention

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Abstract

One remarkable merit of EV is the electric motor's excellent performance in motion control. This merit can be summarized as: (1) torque generation is very quick and accurate, (2) output torque is easily comprehensible, (3) and motor can be small enough to be attached to each wheel. To utilize these advantages of EV, we have carried out some studies on motion control of EV. Our final target is to enhance the vehicle stability of EV, with feedback control techniques and motor's performance. First of this paper, the feedback control of wheel velocity is discussed. The purpose is to avoid the dangerous wheel skid during rapid brake and acceleration, similar to that of ABS (anti skid brake system) or TCS (traction control system). This proposed controller increases the wheel inertia equivalently. The driven wheel seems to have "large" inertia, and this prevent the sudden wheel skid. We have carried out some experiments with actual EV and slippery road to confirm this effect. In the next part, the vehicle lateral stability will be discussed. As commonly known, the vehicle lateral motion can be sometimes unstable, especially cornering and/or braking on snowy or wet road condition. As mentioned above, each wheel of EV can be attached one motor, such as in-wheel motor. Our simulation results show that this "4 wheel-motored" EV can prevent such unstable lateral motion on the slippery road, with the autonomy stabilization of each wheel with wheel velocity control. At last, we introduce the cooperative control of regenerative control and hydraulic ABS. In this method, regenerative braking is controlled to have "large" inertia against hydraulic braking torque. This is a minor loop controller, which enhances the short-time dynamics of ABS and decrease the braking distance.

1 Introduction

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

1. ***Torque generation 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.

2. ***Output torque is easily comprehensible.***

   The second advantage will contribute a great deal to the road condition estimation. 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 [1] [2].

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

   Distributed motor will possibly enhance the performance of DYC (direct yaw moment control) [3] [4]. The yaw moment can be generated more easily and precisely. Even the anti-directional torque generation is possible on left and right wheels.

On the other hand, the control engineering is now developed. If the actuator is fast enough as motor, we can fully apply these advanced theories. Metaphorically speaking, we can control EVs precisely as robots. However, only a few papers were published on this issue [5].

In this paper, we carried out some basic studies mainly on issue 1. To utilize the fast torque response, feedback control of wheel velocity is discussed. Here authors attempt to increase the wheel inertia equivalently during the wheel skidding. Section 3 describes this method with experimental results. In section 4, effect of this method on vehicle lateral stability is studied. Section 5 discusses on the cooperative control of regenerative brake and hydraulic ABS. Section 6 will conclude this paper.

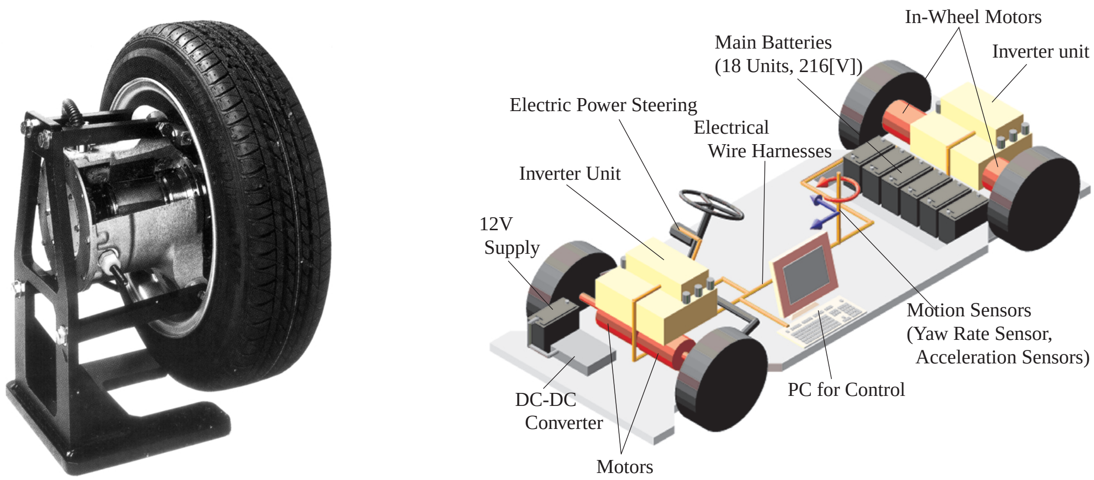

Figure 1: In-wheel motor and our new EV with four in-wheel motors.

2 Slip phenomena and anti skid control methods

Here authors mention about the slip phenomena of wheel. 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. 2), 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. This F_d has nonlinear dependence on the slip ratio λ. Here normalized traction force μ is defined as

$$\mu = \frac{F_d}{N}, \tag{4}$$

where N is the normal force on the wheel. Fig. 3 plots this normalized traction force μ vs. slip ratio.

If large torque rapidly generated on the wheel, or the F_d suddenly drops with changing road condition, then wheel skid occurs. Once skid occurs, slip ratio λ rapidly increases toward 1.0. With such large slip ratio, the driving/braking force F_d decreases as shown in Fig. 3. More serious problem is that, the side force generation on wheel rapidly disappears with increasing slip ratio. This causes unstable vehicle lateral motion, such as dangerous spin motion.

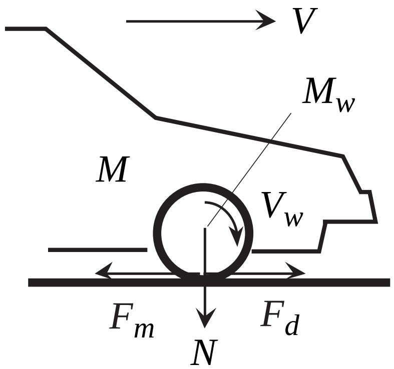

Figure 2: One wheel model.

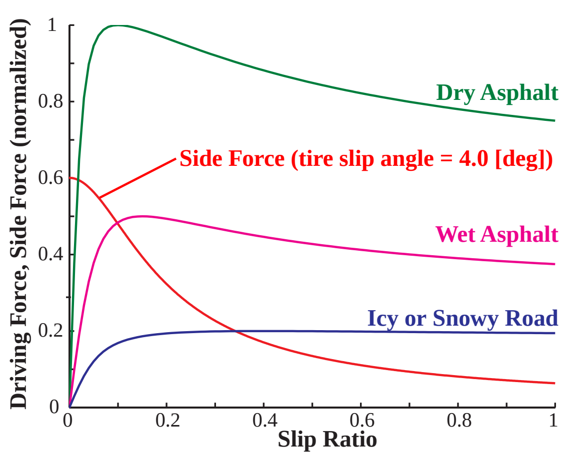

Figure 3: $\mu - \lambda$ curve.

3 Anti skid effect of wheel velocity control

3.1 Controller design

One dominant phenomenon in the wheel skidding is the rapid change of wheel rotating velocity. During the acceleration, the wheel velocity rapidly increases with wheel skidding, and during the deceleration it rapidly drops due to the wheel lock. Therefore, the feedback control of wheel velocity control seems to be effective for skid prevention. Generally, the feedback controller can change the dynamics of the plant or target. Such feedback control requires fast response of actuator, and so it should be suitable to utilize EV's advantage.

First, we derive linear skid model from (1)-(3) and $F_d(\lambda)$ in Fig. 3. This $\mu - \lambda$ curve in a nonlinear one, therefore, perturbation equation for $F_d(\lambda)$,

$$\begin{aligned} \Delta F_d &= \Delta\mu N = a\Delta\lambda & (5)\\ &= a\left(\frac{\partial\lambda}{\partial V}\Delta V + \frac{\partial\lambda}{\partial V_w}\Delta V_w\right) & (6)\\ &= -\frac{1}{V_{w0}}\Delta V + \frac{V_0}{V_{w0}^2}\Delta V_w & (7)\end{aligned}$$

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

$$a = \left.\frac{\partial\mu}{\partial\lambda}\right|_{(V_0,V_{w0})} \tag{8}$$

V_{w0}, V_0 are the wheel velocity and chassis velocity at the operational point, respectively. With (1)-(3) and (7), the transfer function from motor torque F_m to the wheel velocity V_w is

$$P(s) = \frac{\Delta V_w}{\Delta F_m} = \frac{1}{(M_w + M(1-\lambda_0))s}\frac{\tau_w s + 1}{\tau_a s + 1} \tag{9}$$

where

$$\begin{aligned} \tau_a &= \frac{M_w V_{w0}}{aN}\frac{M}{M(1-\lambda_0)+M_w} & (10)\\ \tau_w &= \frac{MV_{w0}}{aN} & (11)\\ \lambda_0 &= 1 - \frac{V_0}{V_{w0}} & (12)\end{aligned}$$

From (9)-(12), the most simple model for almost adhesive wheel ($\lambda_0 \ll 1.0$), $P_{\text{adh}}(s)$, can be described as

$$P_{\text{adh}}(s) = \frac{1}{M + M_w}. \tag{13}$$

On the other hand, for the completely skidding wheel ($\lambda \simeq 1.0$), the dynamics seems to be $P_{\text{skid}}(s)$,

$$P_{\text{skid}}(s) = \frac{1}{M_w}. \tag{14}$$

Based on these equations, we design the feedback controller of Fig. 4 [6]. This controller makes the wheel pretend to be $P_{\text{adh}}(s)$, even if the actual plant $P(s)$ is $P_{\text{skid}}(s)$. In other words, the wheel seems to have "heavy" inertia against the motor torque during wheel skid. As shown in Fig. 4, K_p and τ are the feedback gain and time constant of this controller. Fig. 5 shows the bode diagram from motor torque F_m to the wheel velocity V_w. The upper figure is for adhesive/skidding wheel without controller. The skidding wheel has the relatively "light" inertia. If the proposed controller is applied, this dynamics V_w/F_m is modified as the lower graph shows. It can be easily realized that the wheel has equivalently same dynamics, even if the wheel is adhesive or skidding. This indicates the wheel's insensitive for slip phenomena.

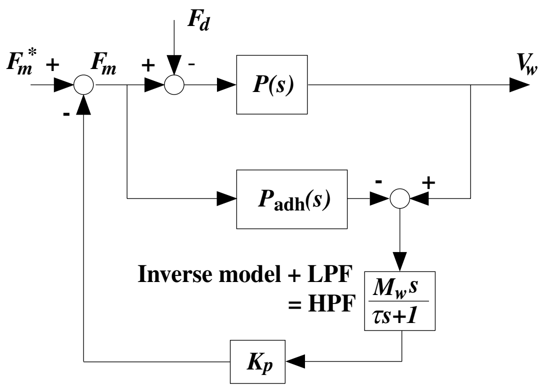

Figure 4: Block Diagram of wheel velocity controller.

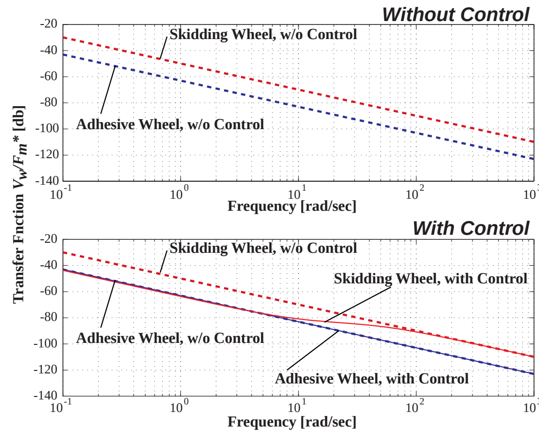

Figure 5: Bode diagram of V_w/F_m, with and without control.

3.2 Experimental results

Experiments of wheel velocity control were carried out for anti skid application. These experiments were carried out with "UOT Electric March-I", which is our laboratory-made EV (Fig. 6, 7). The specification of this EV is shown in Table. 2. 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 (Fig. 6). The peak μ of this test road is about 0.5. This value was estimated based on some other experimental results.

Our experimental vehicle has a series-wound DC motor and an one-quadrant chopper. It means that the electric braking is impossible with our vehicle. Therefore, in this section, we carried out the skid prevention experiments for accelerating vehicle, like skid prevention with TCS. Note that the controller of Fig. 4 will also be effective for braking wheels.

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 control. Fig. 9 plots the wheel and chassis speed. It shows the wheel velocity's insensitivity to the slip status. In another words, 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. The simulation results almost agrees with the experimental results [1], indicating the reliability of simulations in the following sections.

[1] The motor current was saturated in the experiments, with high V_w. At about 5.5[s], the EV reached at the end of the slippery test road and run again on the dry asphalt. These are the reason of the difference between experimental and simulation results.

As mentioned above, the feedback controller changes the wheel dynamics as shown in Fig. 5, then the serious skid is prevented. Therefore, this effect depends on how the wheel dynamics was changed, or depends on $P_{\mathrm{adh}}/P_{\mathrm{skid}}$. For our EV "UOT Electric March-I", this effect can be evaluated about 5.0, which is calculated with M and M_w. Experimental results of Fig. 10 shows that, the growth rate of slip ratio decreased about five times. It means that this controller makes the "slip" about five times as slow as the original dynamics. This experimental result confirms that our controller design process was appropriate one.

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

Motor	**DC Motor**
Rated Power(5 min.)	32.5[kW] (44.3[HP])
Max. Torque	85[Nm]
Gear Ratio	13.5
Battery	**Lead Acid**
Nominal Capacity	92[Ah]
Total Voltage	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)	1800/120[ppr]

* Includes the motor rotor, affected by gear ratio.

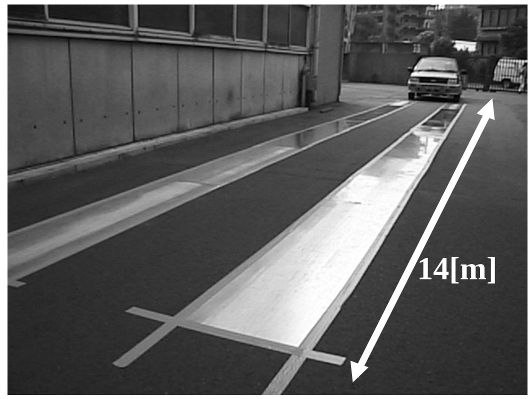

Figure 6: Test low-μ road for experiments.

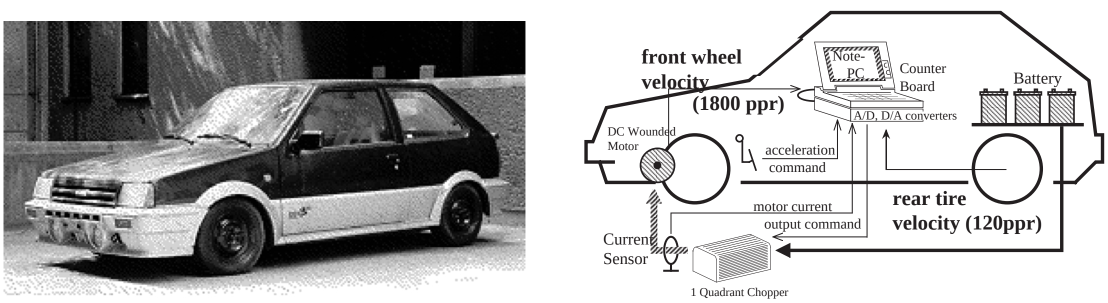

Figure 7: Our experimental vehicle, "UOT Electric March-I".

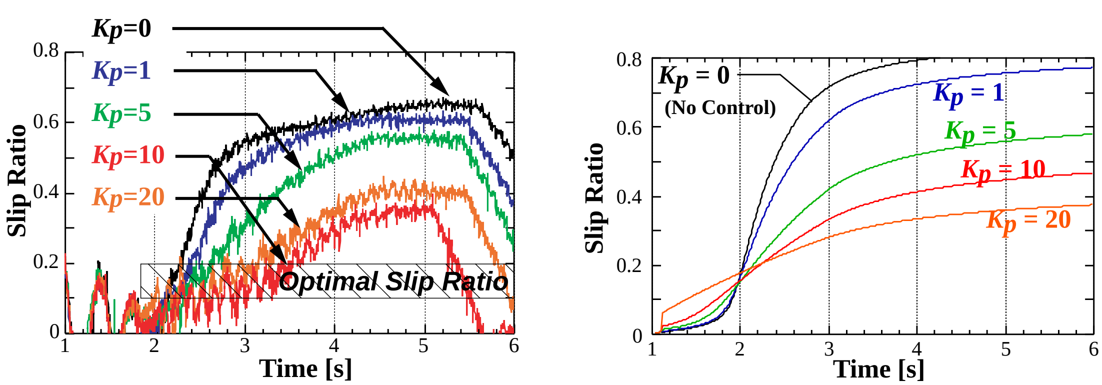

Figure 8: Effect of wheel velocity control for skid prevention with τ=0.1[s] (Left fig.: Experimental results / Right fig.: Simulation results)

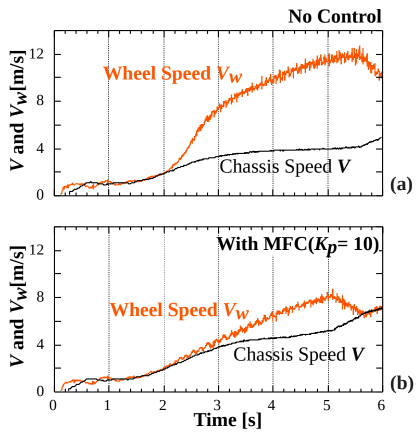

Figure 9: Wheel and chassis velocity with and without control.

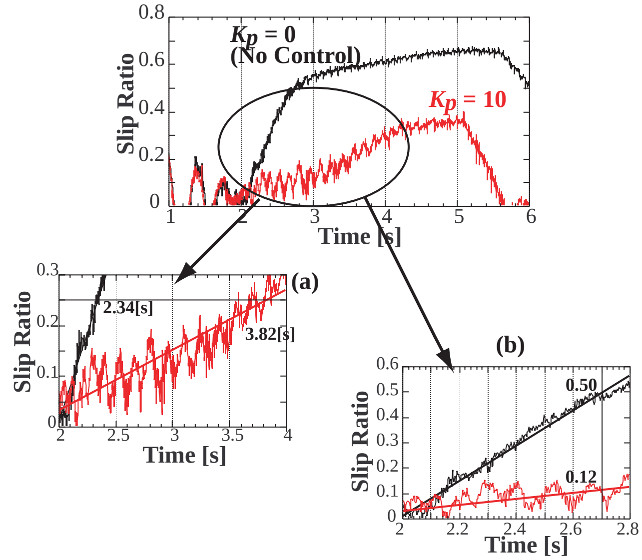

Figure 10: Effect of "slow" slip growth with proposed method.

4 Lateral motion stabilization based on wheel velocity control

In the previous section, wheel velocity feedback was discussed. With this method, wheel seems to have heavy inertia equivalently during slip. This suppresses the rapid increase of slip ratio. Then, what will happen if we apply such method for vehicle in cornering?

As commonly known, the vehicle lateral motion can be sometimes unstable. This instability occurs in such situation as rapid braking during turning the curve, especially with slippery road condition with snowy or rainy weather. Here we assume that the target EV is equipped one motor per one wheel. In-wheel motor is a typical example. We are now manufacturing the actual EV with four in-wheel motors (Fig. 1). With such motor, the wheel velocity can be controlled in each wheel independently. Our simulation results (Fig. 11 - 13) show that this "4 wheel-MFC" can enhance the vehicle's lateral stability. In these simulations, the vehicle 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 inputted 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]. Especially, this wheel skidding is serious at rear-left wheel, since the center-of-gravity is shifted. On the contrary, if the wheel velocity controller is applied, such dangerous spin motion is prevented. The rear-left wheel's torque is most reduced, and this indicates the autonomy stability effect of this method. Note that this method uses only wheel velocities as feedback signals, therefore, differs considerably from conventional chassis control methods like DYC(Direct Yaw Moment Control) [3] [7]. The autonomy stabilization of each wheel, which is achieved with wheel velocity control, enhances the stability of vehicle lateral motion on slippery road.

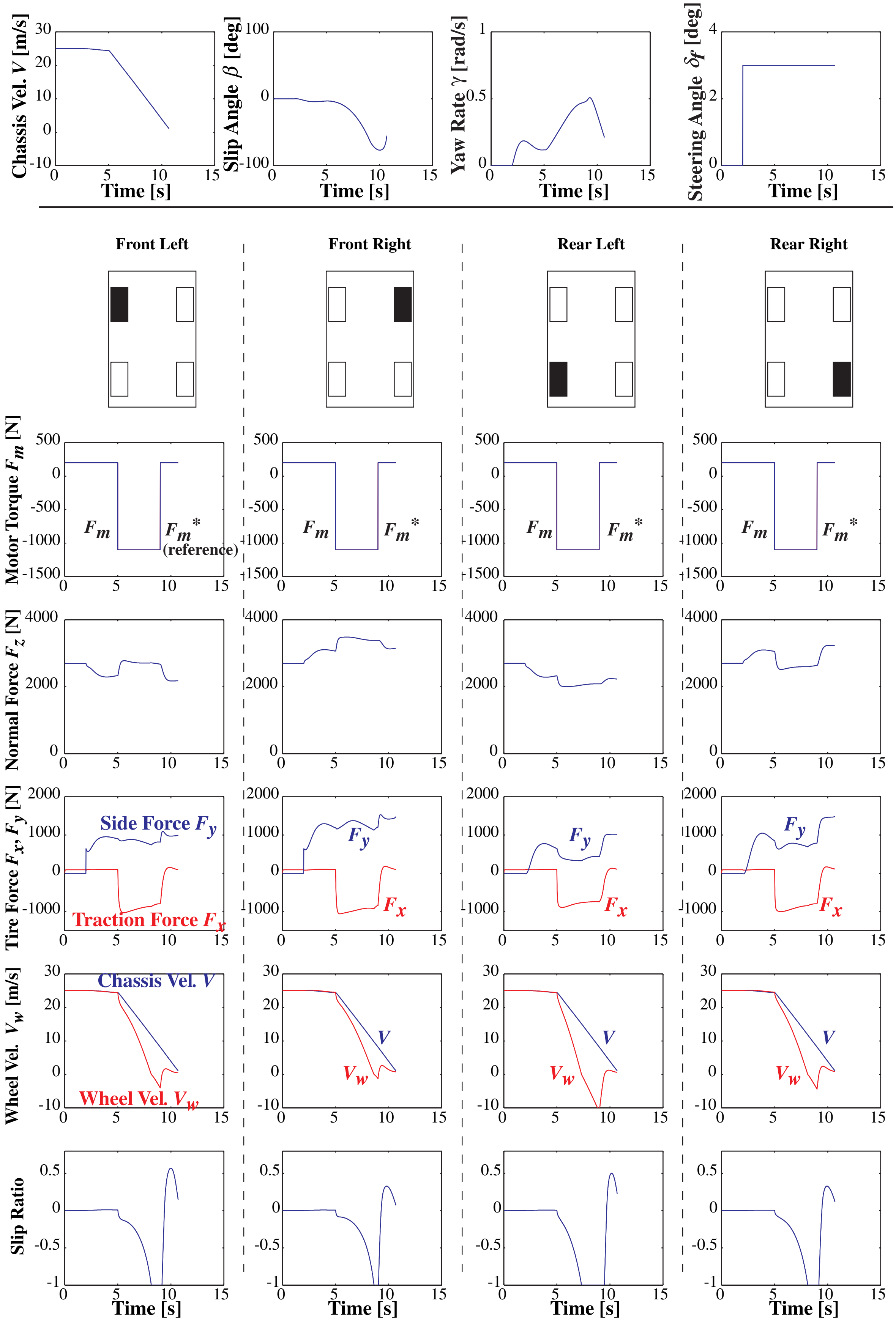

Figure 11: Example of unstable vehicle lateral motion. This is the simulation results of rapid braking on slippery road, during turning the curve.

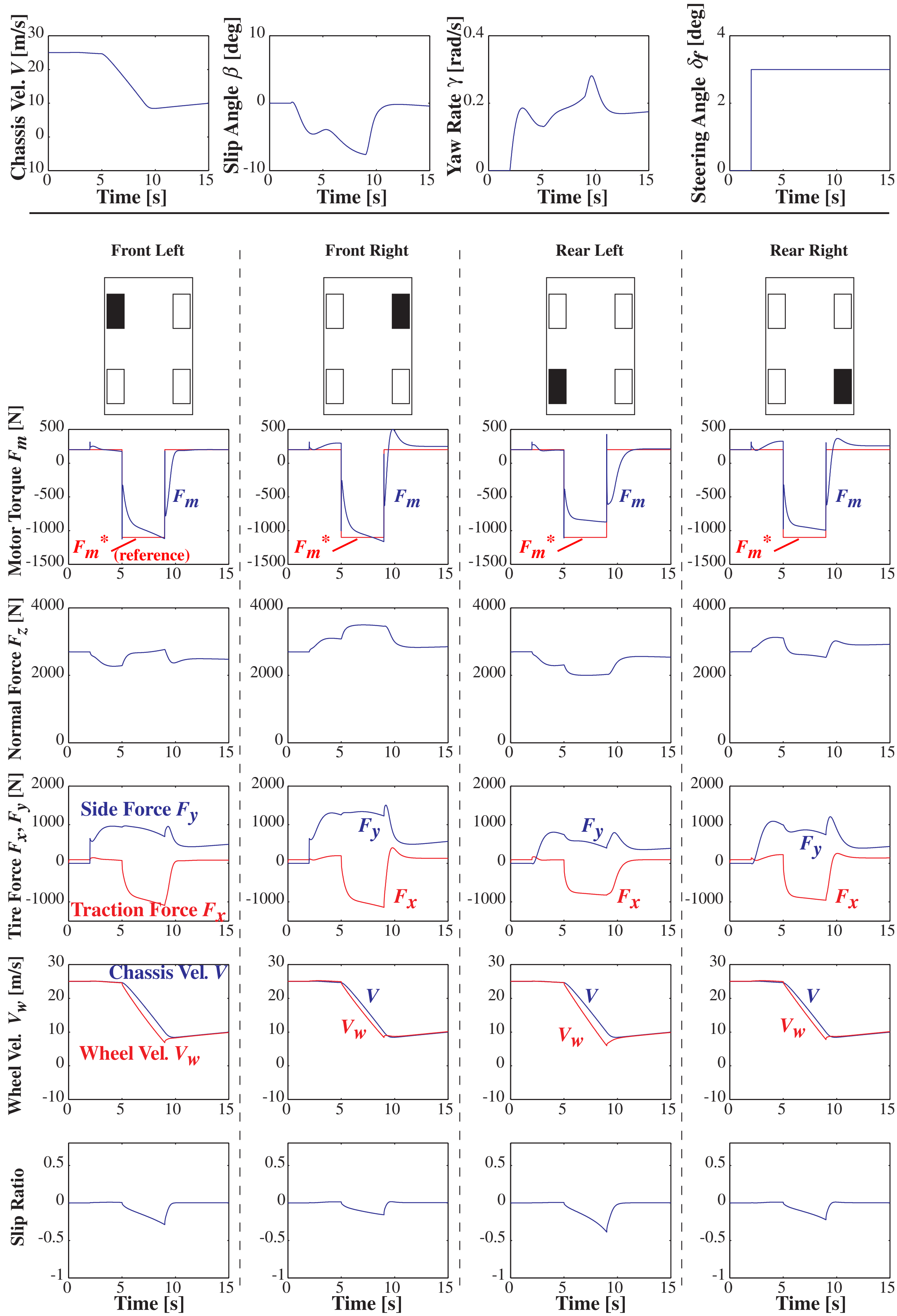

Figure 12: Simulation results of rapid braking on slippery road, during turning the curve with controlled four wheels. The driver's braking torque input is the same as Fig. 11, however, the vehicle is still stable.

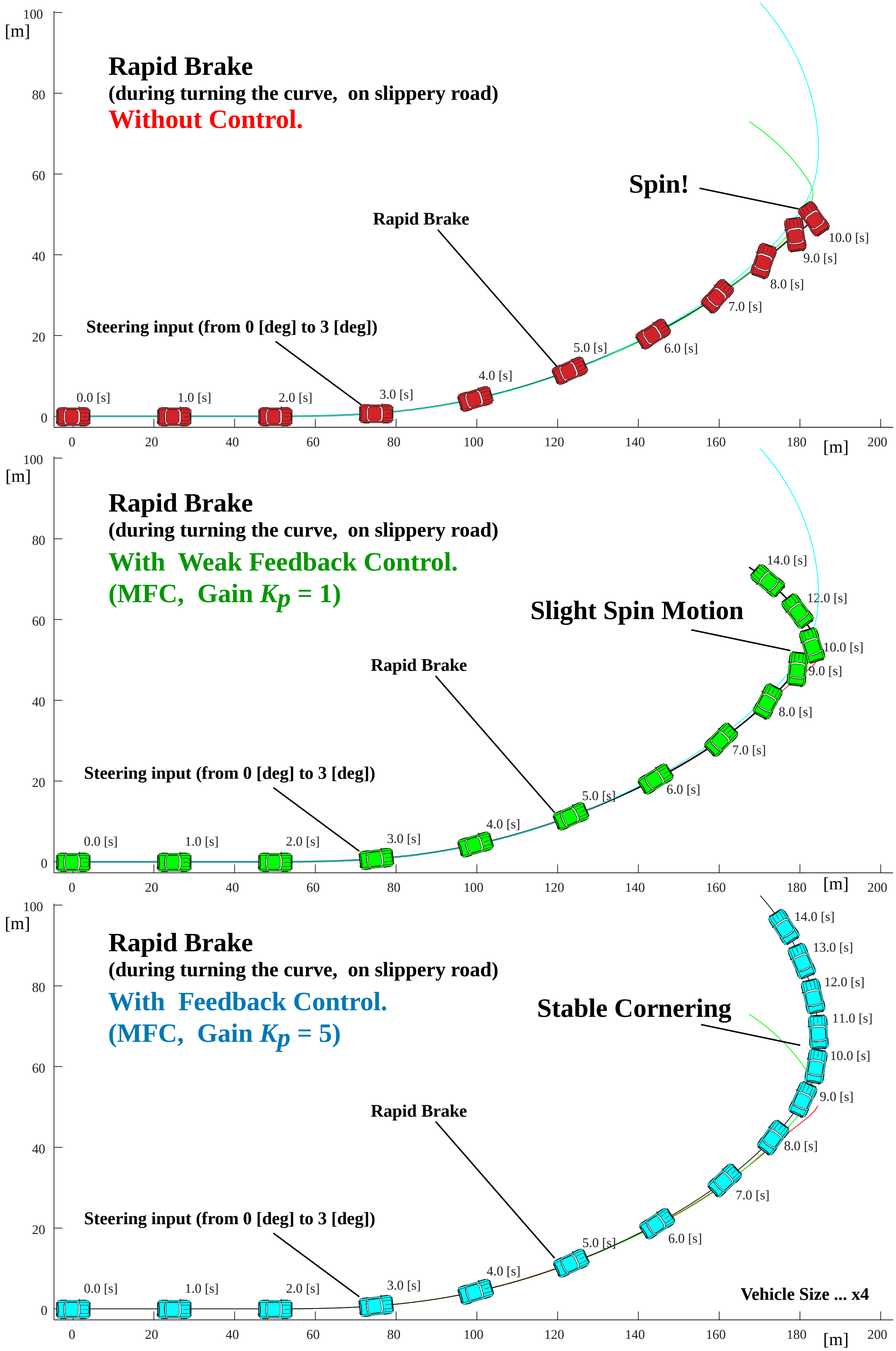

Figure 13: Stabilization effect of "controlled four wheels" is visualized with vehicle's trajectory. The upper one is the results of Fig. 11, and the bottom one is of Fig. 12.

5 Regenerative braking control cooperating with hydraulic ABS

With motor or regenerative braking, fast feedback control can be applied as mentioned above. Such controller can change the dynamics of wheel, for example, change the wheel's equivalent inertia to be quite heavy.

In this section, regenerative braking control cooperating with hydraulic ABS is introduced. In most EVs or HEVs, regenerative braking is generally used with hydraulic braking system. Pure electric braking is not applied at this moment. The reason is the maximum torque limitation of motor, batteries' SOC (state of charge), or expectation for the reliability of mechanical systems. Thus if someone attempt to apply the anti skid method with motor control, cooperation or interference between regenerative and hydraulic braking must be considered. ABS was well studied and practically applied [8]. Most conventional systems sense the acceleration of wheel velocity and/or slip ratio, and control the wheel brake cylinder's hydraulic pressure. However, it is still difficult to prevent large drop of wheel velocity at the beginning of control [9]. Therefore, we intend to improve such short-time performance of ABS with motor or regenerative brakie control. Here we show some idea to do such control.

5.1 Regenerative braking controller design

One of the problems of hydraulic ABS is the delay in the skid detection or actuator response. Thus, here we aim to compensate the wheel's short-time dynamics within such delay time.

Fig. 14 shows the block diagram of proposed controller. Hydraulic system generates braking torque F_{ABS}, based on the hydraulic braking torque reference F^*_{ABS}. The total braking torque F_{brake} is

$$F_{\mathrm{brake}} = F_{\mathrm{motor}} + F_{\mathrm{ABS}}, \tag{15}$$

where F_{motor} is the regenerative braking torque, output of proposed controller. We assume the purpose as below:

(1) If wheel is adhesive: ABS controller do nothing, therefore, $F_{\mathrm{ABS}} = F^*_{\mathrm{ABS}} + \Delta$, where Δ denotes the uncertainty factor such as pad secular variation. ***In this case, motor torque should be $F_{\mathrm{motor}} = F^*_{\mathrm{motor}}$.*** Both F^*_{ABS} and F^*_{motor} are required by upper layer controller, which decides how to achieve the driver-requiring deceleration rate, with maximizing the energy efficiency of regenerative brake.

(2) If wheel is skidding: ABS controller works. ***The actual F_{ABS} is assumed to be unmeasurable.*** Energy efficiency of regenerative brake is not important issue in this case, therefore, no need to achieve $F_{\mathrm{motor}} = F^*_{\mathrm{motor}}$. The feedback controller should varies F_{motor} actively and dynamically, to improve the ABS performance. ***Constraint: the feedback controller have no information about ABS controller, and we can do nothing on ABS control algorithm.***

In addition, ***regenerative brake controller is assumed to be a single controller.*** The algorithm is always the same, and it is not switched depending on the ABS on/off status. For these purposes and constraints, we take a controller design strategy which is quite similar to the previous one in Sec. 3 This feedback controller can be described with $P_n(s)$ and $Q(s)$,

$$P_n(s) = \frac{1}{(M + M_w)s}, \quad Q(s) = Ms\frac{1}{\tau s + 1}. \tag{16}$$

With these feedback controller and τ=0.1[s], the transfer function $H(s)$ from F_{ABS} to F_{brake} can be changed as Fig. 15. [2] Fig. 16 plots $H(s)P(s)$, which is the transfer function from F_{ABS} to V_w. These bode diagrams are calculated with simple wheel model $P_{\text{adh}}(s)$ and $P_{\text{skid}}(s)$, defined in (13) and (14), respectively.

The remaining problem of this controller is the steady-state gain for adhesive wheel, $H(0)_{\text{adh}}$,

$$H(0)_{\text{adh}} = \frac{M + M_w}{2M + M_w} \neq 1.0. \tag{17}$$

Eq. (17) means that the transmission of hydraulic braking torque is blocked with motor torque. To prevent this blocking, the feedforward controller C_{FF} is designed as,

$$\begin{aligned} C_{\text{FF}}(s) &= \left(1 - H_{\text{adh}}(0)\right)F^*_{\text{ABS}} + F^*_{\text{motor}} \\ &= \frac{M}{2M + M_w}F^*_{\text{ABS}} + F^*_{\text{motor}}. \end{aligned} \tag{18}$$

With this feedforward controller, the total braking torque F_{brake} during adhesive decelerating come to be

$$F_{\text{brake}} = F^*_{\text{motor}} + F_{\text{ABS}}. \tag{19}$$

Note that response to both reference and disturbance (=F_{ABS}) is concerned here, although response to only the reference was concerned in Sec. 3

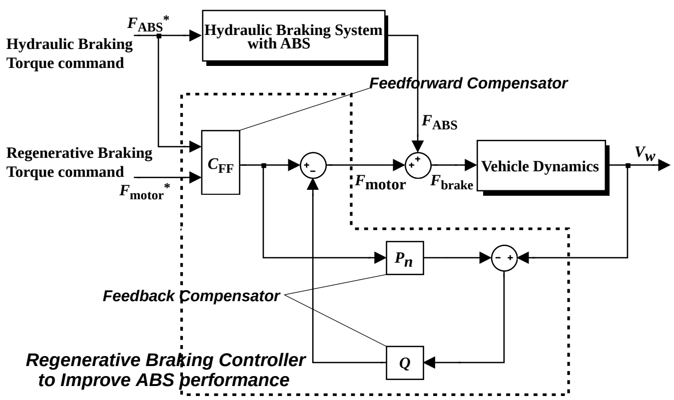

Figure 14: Block diagram of proposed controller.

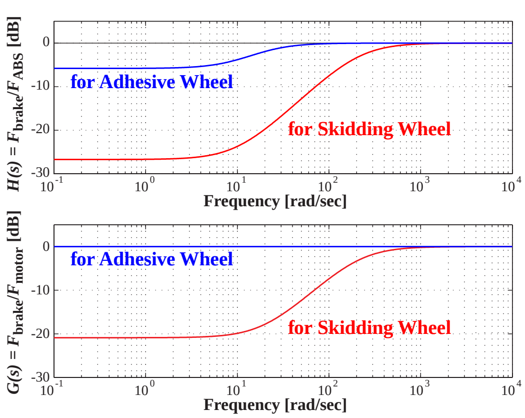

Figure 15: Bode diagram of $H(s), G(s)$.

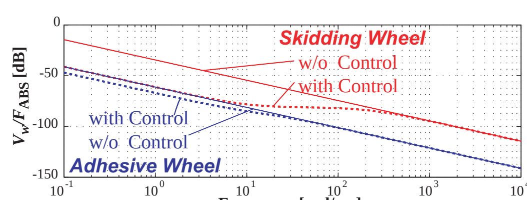

Figure 16: Bode diagram of $H(s)P(s)$.

[2] Of course, $H(s)$ is a sensitivity function.

5.2 Simulation results

Simulations are carried out to confirm the effectiveness of proposed controller. These simulations are with one wheel vehicle model (Fig. 2) and nonlinear Magic Formula tire model. Table 2 shows the parameters. ABS controller is modeled simply as bang-bang controller, with time delay in Table 2.

Fig. 17 shows the simulation results with adhesive road condition ($\mu_{\text{peak}} = 1.0$). The motor generates the commanded regenerative braking torque, which is required by upper layer controller, for example to maximize the energy efficiency. The feedback controller does not block or interfere with the hydraulic braking torque.

Fig. 18 shows the results with slippery road condition ($\mu_{\text{peak}} = 0.5$). The left column shows the results with only hydraulic ABS, and the right column shows the results with hydraulic ABS and proposed controller. Fig. 18 shows that the slip ratio oscillation can be suppressed with proposed regenerative brake controller. The braking force is enlarged by this effect, therefore, the braking distance can be reduced by 20 %.

Vehicle weight (M)	1100[kg]
Wheel inertia (M_w)	53.3[kg]
Dead time in skid detection (τ_{Ds})	50[ms]
Dead time in ABS torque response (τ_D)	20[ms]
1^{st} order Delay in ABS torque response (τ_m)	50[ms]
Max. of Hydraulic Braking torque	4000[N]
Max. of Regenerative Braking torque	2000[N]
1^{st} order Delay in Motor torque response	1[ms]

Table 2: Parameters in the simulations.

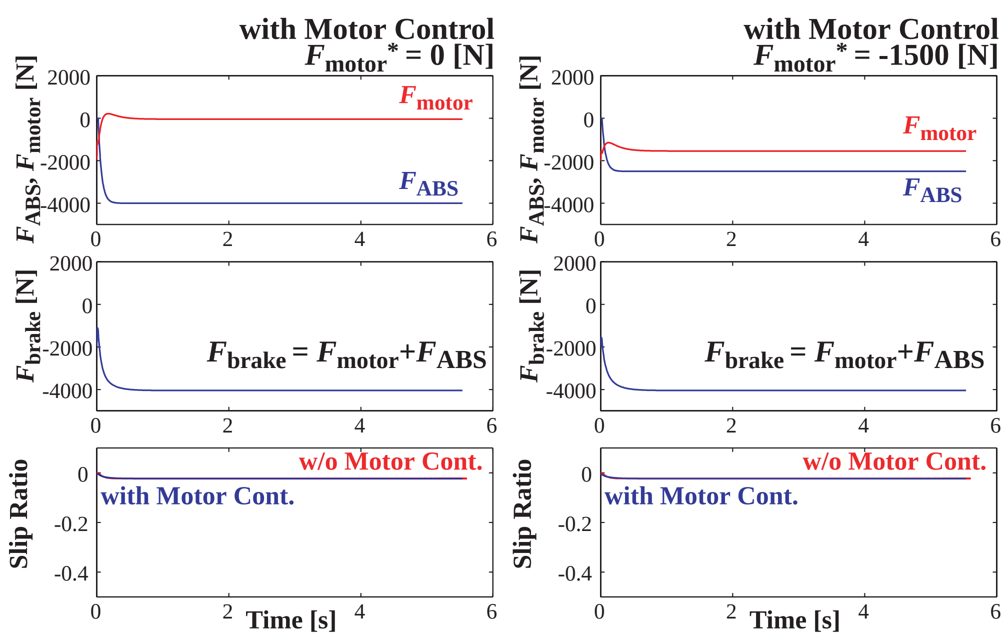

Figure 17: Simulation results with adhesive road.

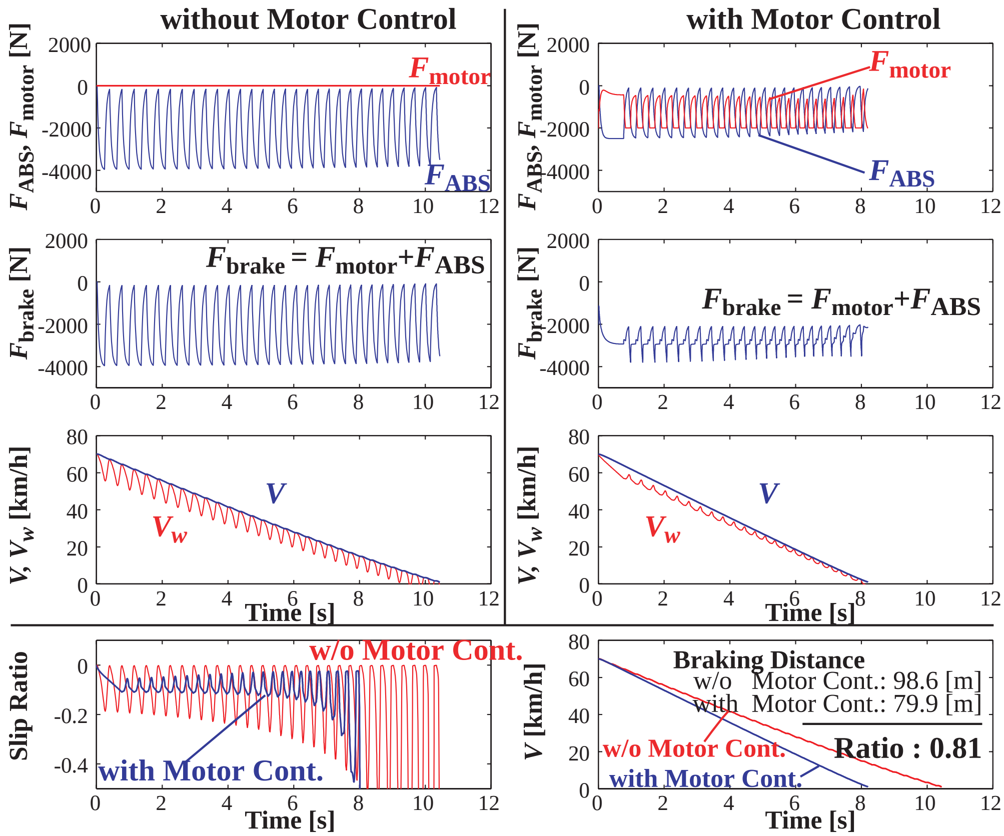

Figure 18: Simulation results with slippery road. （F^*_{motor} = -1500 [N]）

6 Conclusion

In this paper, we described the advantage of EVs in motion control issue. The goal is to enhance the vehicle stability with feedback control of motors. We proposed the wheel velocity controller for skid prevention, and confirmed the effectiveness with experiments with actual EV. This controller can change the wheel's dynamics, or increase the equivalent inertia of wheel. Such feedback control is difficult with slow actuator like engine or hydraulic brake. The proposed feedback controller can enhance the vehicle lateral stability, as we showed with simulations. The motor control loop is a fast minor feedback loop in a total chassis control system, as depicted in Fig. 19. This minor loop will enhance the stability of upper layer chassis control system, such as DYC. Note that DYC can be easily applied in EV with two or four motors. Our basic concept is to apply the minor feedback loop with motor control. We also showed another example of this concept. The novel regenerative braking controller was designed with this concept, and was confirmed to improve the performance of hydraulic ABS. For further studies, another experimental studies are required on this issue, "the minor feedback loop with motor". It will be carried out with our new EV.

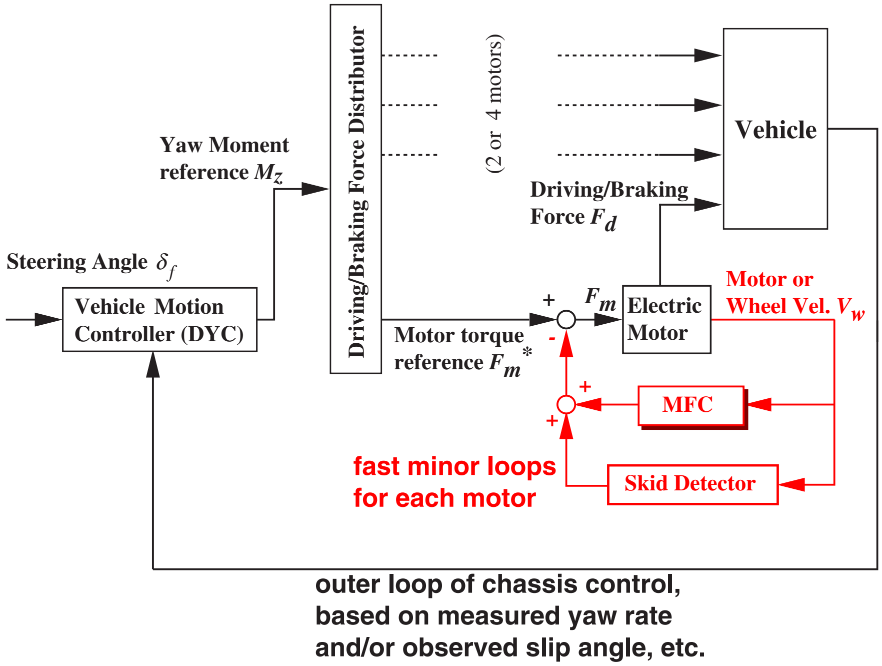

Figure 19: Our concept: minor-loop controller for each wheel.

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