Vehicle Stability Improvement Based on MFC Independently Installed on 4 Wheels
-Basic Experiments using "UOT Electric March II"-

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Abstract

The focus of our research is on exploiting the excellent control characteristics of the electric motor in realizing advanced vehicle motion control. To this end, we have built an Electric Vehicle (EV) fitted with 4 in-wheel motors. Rapid independent torque control of each motor is realised through a real-time Operating System. With this vehicle we performed experiments to verify control methods which we have formulated, e.g., Model Following Control (MFC). The detection of road conditions and wheel-skid will be planned, too. All these new techniques are possible only on the EV due to its rapid and accurate torque response.

Key words: Electric Vehicle, Motion Control, Anti-lock Braking System, Direct Yaw Moment Control.

1 Introduction

Recently, much research on automobiles with next generation power-trains has been carried out in automobile industries. The improvement of electric vehicles (EVs) has been amazing, and nowadays we see a lot of next generation cars like Prius(TOYOTA) and Insight(HONDA) on the road. The focus of EV research has mainly been on energy and environmental problem. But we overlook other advantages of EVs. These advantages can be summarized as follows,:

1. Electric motor can generate bi-directional torque (accelerating and decelerating) very quickly and accurately.
   This is the essential advantage. The electric motor's torque response is 10-100 times as fast as that of the combustion engine and hydraulic braking system. If we can utilize the fast torque response of the electric motor, applications like "Super TCS"(function as both ABS and TCS) is possible [1].
2. Motor torque can be measured easily.
   The torque generation process of the combustion engine and hydraulic brake contains many uncertainities, so it is difficult to acculately measure their output torque. But the electric motor's output torque can be measured easily. Therefore, we can construct a "driving force observer" which observes driving/braking force between the tire and road surface in real-time [2][3]. This advantage will contribute a great deal to several applications like road condition estimation.
3. More than one electric motor can be mounted on each EV.
   Electric motors like in-wheel motors are very small. Therefore a motor can be attached to each wheel. In conventional automobile control, Vehicle Stability Control(VSC) like Direct Yaw moment Control(DYC) is very complicated [4][5]. But in EVs, by mounting two or four in-wheel motors, realization of DYC is much easier and its quality is more superior.

In conclusion, these adavantages of electric motor give rise to the possibility of vehicle motion control in EVs. In automobile industies, active vehicle control is presently the principal theme. Electrical engeneering can contribute much to this novel and important theme. Fig.1 shows the basic idea behind our novel proposal :an integrated system with "minor feedback loops” and “total chassis controller”.

In order to prove the advantage of utilizing electric motor in vehicle stability control, we have constructed a novel experimental EV ”UOT Electric March II”. This EV will be introduced in the following section.

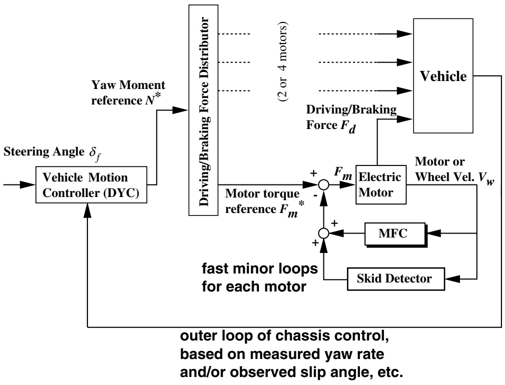

Fig. 1. Our basic idea: Total system with minor feedback

2 Novel Experimental Electric Vehicle ”UOT Electric March II ”

Our EV ”UOT Electric March II” is constructed for the purpose of experimenting with novel control methods. The most characteristic point of this EV is that it is mounted with one motor in each wheel. Therefore, we can control each wheel torque independently. Of course regenerative braking is available. We have built this EV ourselves, by remodeling the ”NISSAN March” which is available on the market.

Table1 is a summary of ”UOT Electric MarchII”'s specifications. The electric motor in this vehicle is PM motor. This type of motor is called ”in-wheel motor”(Fig.2), because the motor has an inbuilt drum brake and a reduction gear. Thus the motor unit is as compact as the wheel. Two motors are placed at the ends of each driving shaft, and attached to the base chassis (Figs.3 and 4). The electric motors are controlled by on-board PC's. ”UOT Electric MarchII” has two PC's. They are linked to several sensors, for example, fiber-optical gyro, acceletion sensor and so on. Motion controllers like MFC is installed in these PC's. The PC's output motor torque command, and two inverter units generate the motor torques on demand. This precise torque generation is achieved by the motor current controller in the inverter units. In order to detect steering angle, this EV is outfitted with EPS(Electric Power Steering).

Table 1. Specifications of “UOT Electric March II”.

Drivetrain	**4 PM Motors / Meidensya Co.**
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.

The battery used in this EV is lead acid battery. ”UOT Electric MarchII” is mounted with 19 batteries as the main power source (9 batteries in the bonnet, 10 batteries in the cabin.), and 1 battery as the sub power source (Figs.2 and 6).

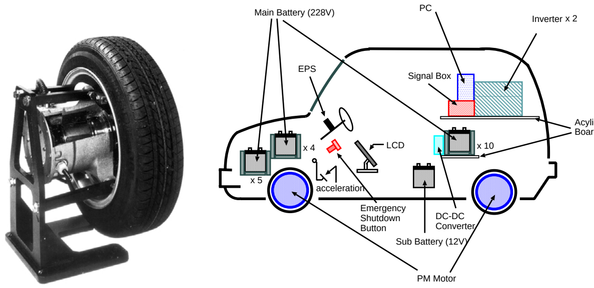

Fig. 2. In-wheel motor / Configuration of ”UOT Electric March II”.

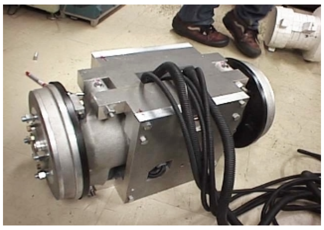

Fig. 3. Front Motors

Fig. 4. Rear Motors

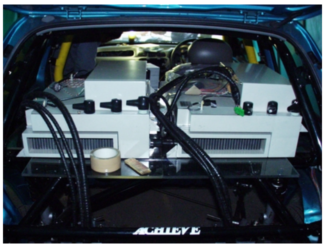

Fig. 5. Inverters

Fig. 6. Batteries

3 Model Following Controller for EV

Using the fast response of the electric motor, we have proposed some anti-slip controllers: ”Slip Ratio Controller” and ”Model Following Controller”.

These are feedback controllers. Feedback control changes the mechanical system. In this section, we discuss the Model Following Controller "MFC".

3.1 Linear Slip Model

Generally, slip ratio λ is given by,

$$\lambda = \frac{V_w - V}{\max(V_w, V)} \tag{1}$$

Where V is the vehicle chassis velocity, and V_w is the wheel velocity. $V_w = r\omega$,where r, ω are the wheel radius and rotational velocity, respectively.

Motion equations of one wheel model (Fig.7) can be reperesented as,

$$M_\omega \frac{dV_\omega}{dt} = F_m - F_d(\lambda) \tag{2}$$

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

In these equations, air resistance and rotating resistance are ignored. M is the vehicle weight, M_w is the mass equivalent value of the wheel inertia, F_m is the force equivalent value of accelerating/decelerating torque, and F_d is the driving/braking force between the wheel and the road surface. F_d is a function of λ(Slip Ratio) as is shown in Fig.8.

In order to design the anti-slip controller, nonlinear property in the $\mu - \lambda$ curve should be linearized. We consider small variation around the operational point.

$$dF_d = Nd\mu = aNd\lambda \tag{4}$$

$$= -\frac{1}{V_{\omega 0}}dV + \frac{V_0}{{V_{\omega 0}}^2}dV_\omega \tag{5}$$

$V_{\omega 0}$ and V_0 are the wheel velocity and vehicle velocity at the operational point respectively. a is the gradient of $\mu - \lambda$ curve described as

$$a = \frac{d\mu}{d\lambda} \tag{6}$$

Using (1)−(6),we obtain the transfer function from F_m to V_ω as follows.

$$P(s) = \frac{dV_\omega}{dF_m}$$

$$= \frac{1}{(M_\omega + M(1-\lambda_0))s}\frac{\tau_\omega s + 1}{\tau_a s + 1} \tag{7}$$

$$\tau_a = \frac{M_\omega V_{\omega 0}}{aN}\frac{M}{M(1-\lambda_0) + M_\omega} \tag{8}$$

$$\tau_\omega = \frac{MV_{\omega 0}}{aN} \tag{9}$$

In these equations, λ_0 is the slip ratio at the operational point.

Finally, we obtain the simplest transfer functions.

$$P_{adh} = \frac{1}{M + M_\omega}\frac{1}{s} \tag{10}$$

$$P_{skid} = \frac{1}{M_\omega}\frac{1}{s} \tag{11}$$

In the next section, we will discuss how to design the Model Following Controller "MFC".

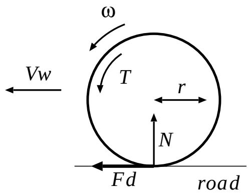

Fig. 7. One Wheel Model

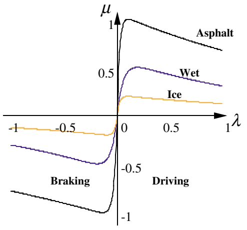

Fig. 8. Typical $\mu - \lambda$ Curve

3.2 Controller Design

In this section, we design the Model Following Controller. When the a vehicle starts skidding, the wheel velocity changes rapidly. For example, if vehicle starts skidding during acceleration, its wheel velocity increases rapidly, and during deceleration, it decreases rapidly due to the wheel lock. According to equation (11) the rapid change of wheel velocity is observed as a sudden drop of wheel inertia. Based on this point view, we design the feedback controller "Model Following Controller" as in Fig.9. Using (10) as the nominal model, this controller can suppress sudden drop of inertia. Applying this controller, the dynamics of the skidding wheel becomes close to that of the adhesive wheel. In other words, the wheel to which the proposed controller is applied becomes insensitive to the slip phenomenon.

In the following section, we apply our proposed controller to "UOT Electric March II".

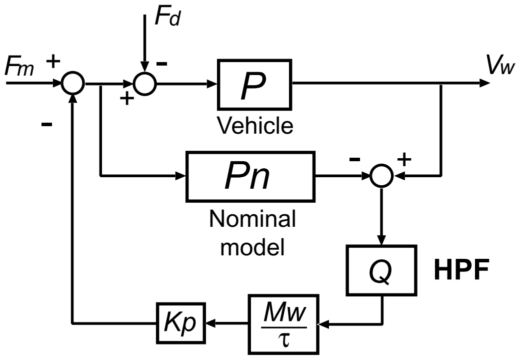

Fig. 9. Block diagram of the proposed feedback controller "MFC"

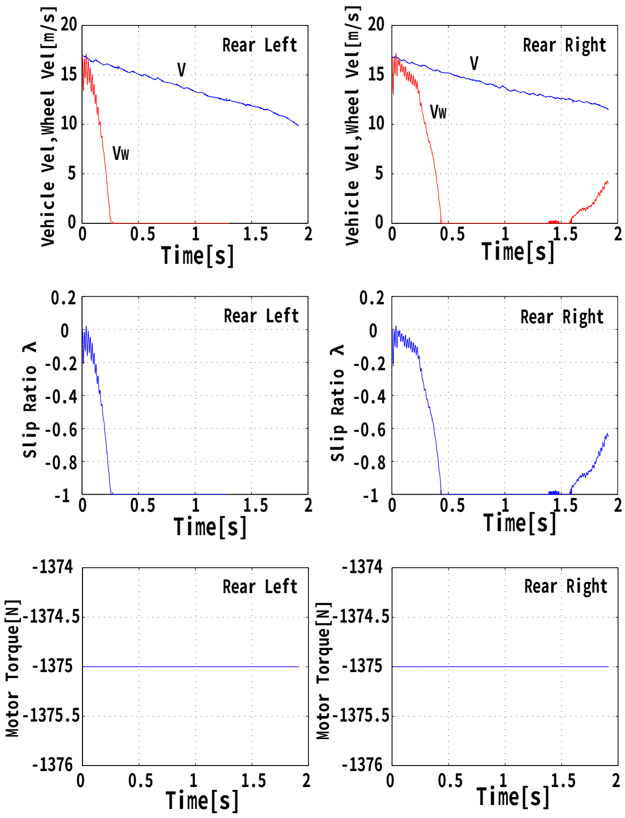

Fig. 10. Wheel lock in rapid braking "without MFC"

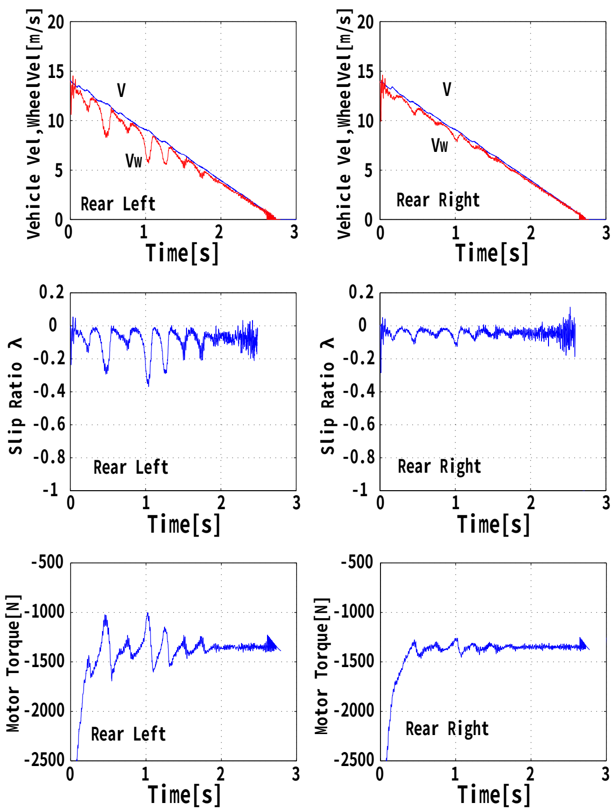

Fig. 11. Stable braking with our proposed controller "MFC"

4 Experimental Results of MFC with "UOT Electric March II"

Fig. 12. Braking Experiment of "UOT Electric March II"

4.1 Improvement in Braking Performance with MFC

In this section, we discuss the experimental results. In the first experiment, sudden brake is applied on slippery low μ road (Fig.12). μ_{peak} of the experimental road is about 0.5.

Figs.10 and 11 show the experimental results. In these experiments, "UOT Electric March II" decelerated suddenly on the slippery test cource. Without control, the wheel velocity rapidly decreased and the vehicle's wheels were soon locked (Fig.10). On the contrary, the change in wheel velocity is relatively slow when the proposed method is applied(Fig.11). The vehicle's wheels did not lock, and the vehicle stopped safely. In this case, the wheel equivalent inertia during the wheel skidding became "heavy" by the effect of MFC, and rapid increase of the slip ratio could be suppressed, and wheel lock were finally avoided.

4.2 Vehicle Stability Improvement with MFC

In the previous section, we discussed the wheel velocity feedback method "MFC". This method suppresses the rapid change in slip ratio and wheel velocity. In this section we will discuss what happens if we apply MFC to each wheels when the vehicle is turning on slippy road. It is common for vehicle's lateral motion to fall into an unstable state, when sudden braking or turning is commanded on slippery road. In these experiments, "UOT Electric March II" did a turn on a slippery road, known as the skid pad. The rear-wheel velocities are controlled independently by the 2 rear motors. ("UOT Electric March II" has one motor mounted on each wheel.)

At first "UOT Electric March II" was turning normally in the clock wise direction. The turning radius is about 25-30[m] and chassis velocity is about

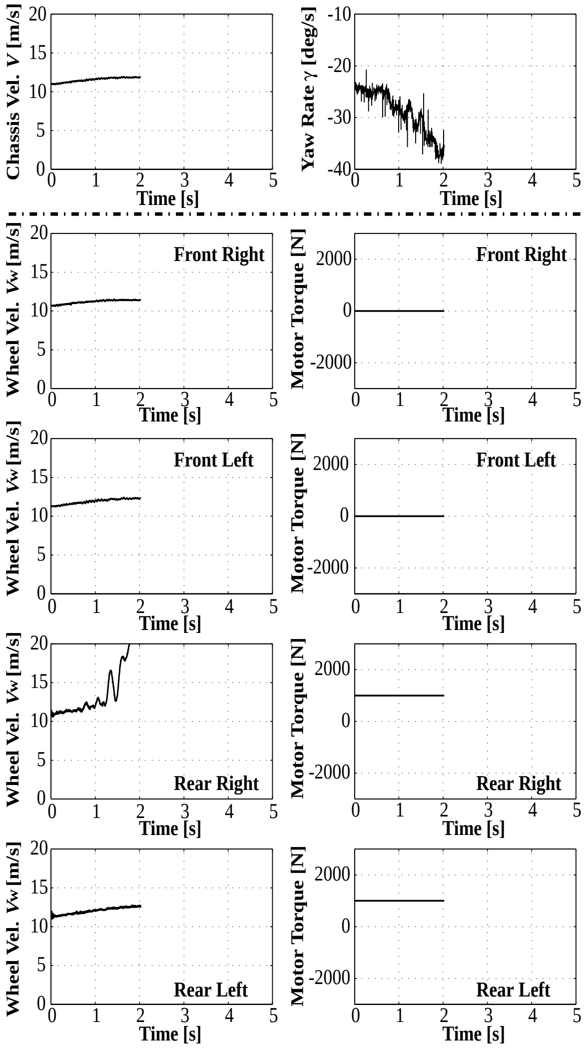

Fig. 13. Unstable turning with sudden acceleration ”without MFC”

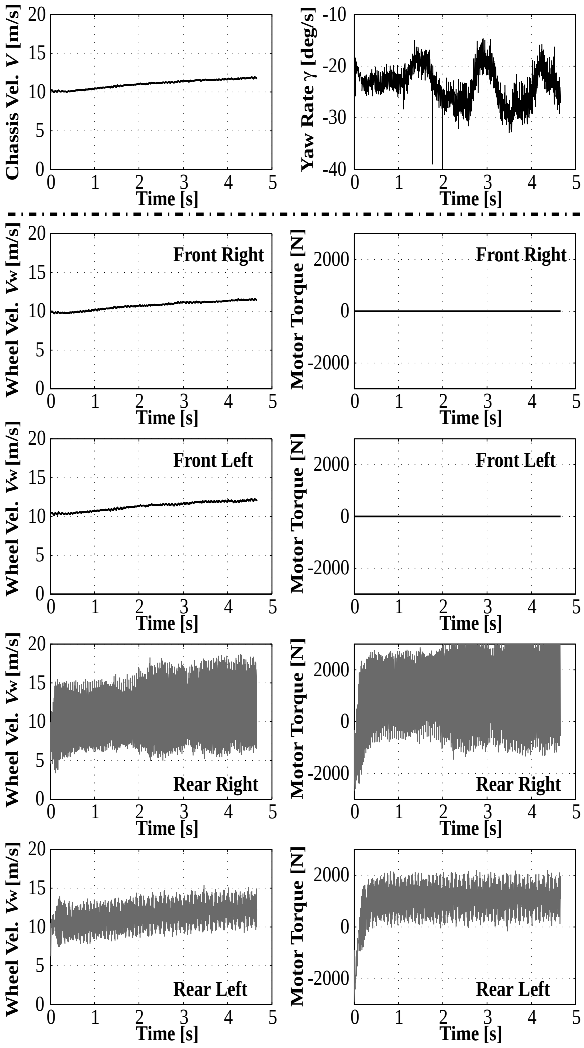

Fig. 14. Vehicle stabilizing effect of our proposed controller ”MFC”

40[km/h]. These values are close to the unstable region. In these experiments, acceleration torque of 1000[N] was applied to the 2 rear motors. Without MFC, this rapid acceleration torque causes instability (Fig.13). The rear right wheel began skidding dangerously. Then the yaw rate γ grew unstable as shown in Fig.13. This vehicle was in spin motion and completely out of control.

On the contrary, such dangerous vehicle motions could be prevented with our proposed method ”MFC”. Figs.14 and 15 show this effect clearly. And Fig.16 is a comparison of the vehicle’s trajects. It shows that the MFC controller prevents spin out due to excessive over steer.

In this case the controllers on rear-right and rear-left are the same but independent from each other, yet vehicle stability is preserved. In other words, autonomous stabilization of each driven wheel was achieved, and vehicle lateral stability was enhanced, as is observed in DYC.

One of the remaining problems is the high-frequency oscillation of the rear wheels. It appears in Figs.14 and 15. It is propably due to the design of the controller’s parameters. We will solve this problem in our next experiment.

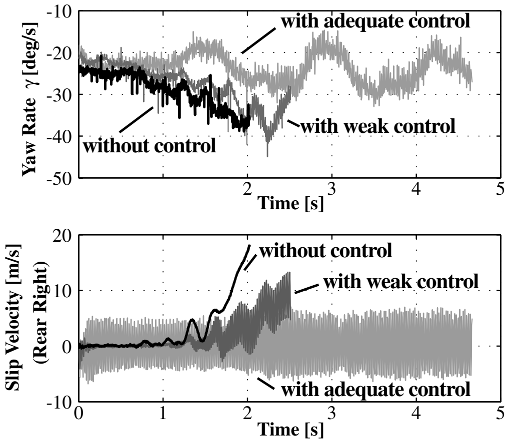

Fig. 15. Comparison of Vehicle Value ”γ,V_w”

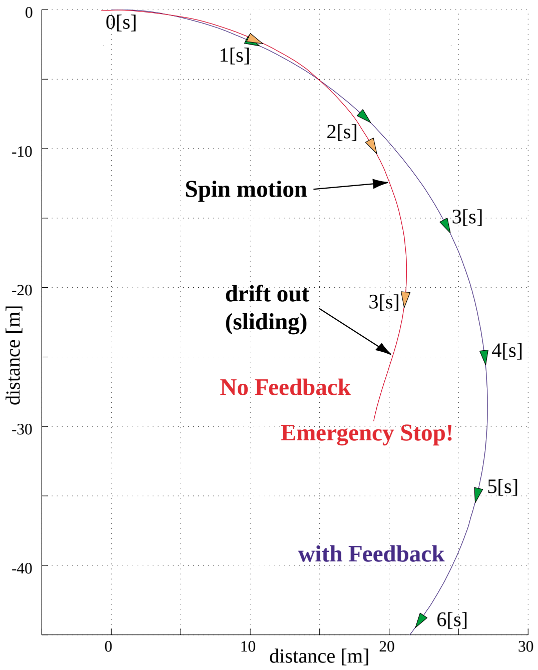

Fig. 16. Stabilizing Effect of "MFC Controller"

5 Conclusion

In this paper, we introduced our novel experimental EV "UOT Electric March II". This new 4 motored EV will play an important role in our novel motion control studies. As the first attempt, we proved the effectiveness of "MFC" using the vehicle.

The most remarkable point of our research is in utilization of the electric motor's advantage: quick, accurate and distributed torque generation. Recent concerns on EV is mainly on energy and environment, but we believe that, in future, high performance vehicle stability control will be the major topic, which can be firstly realized by EV's.

6 Future Research

In this paper, we discussed "MFC", but we have studied on several other motion control issues revolving around EVs. For example, "Road Condition Estimation"[2], "Vehicle Velocity Estimation", " β (Chassis Slip Angle) Estimation" "Decoupling of Direct Yaw Moment Control and Active Front Steering" and "Hybrid ABS"[6].

In the near future, we will carry out experiments on these topics using "UOT Electric March II".

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