Stabilizing Control of Vehicle Motion Using Small EV driven by Ultra Capacitor

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Abstract— **This paper presents the stabilizing control of electric vehicle motion, driven only by "Electrical double layer capacitors (EDLC)" as the energy source. This vehicle provides easy experiment of electric vehicle motion control, since it has extremely simple structure and helps us to perform some experiments easily taking advantage of the peculiar characteristic of large current charging. It shortens the charging time, which makes any experiments convenient and comfortable. In this paper, the basic characteristic of capacitor, basic driving experiment and our vehicle system are shown, at the last our future plans on vehicle system and motion control will be discussed.**

I. INTRODUCTION

In autumn 2003, "Japan Electron Optics Laboratory" announced that they developed an ultra capacitor whose energy and power density were raised as much as 10 times and equivalent to NiMH battery. It is said that the energy storage devices opened the gate into the completely new age. Ultra capacitor has the following characteristics.

- It can be charged and discharged without heat generation because it is not based on chemical reaction.
- Capacitor's voltage level tells us the remaining of energy level very precisely.
- Capacitor is very tough to endure the repetitions of charging and discharging.
- Capacitor is environmental friendly for not using heavy metals.
- The response of current absorption is very quick.

Generally, capacitors have been used as backup batteries of mobile PC's, printers, UPS's, etc. In the field of automobile, fuel-cell (hybrid) vehicles use capacitors not only for absorbing the regenerated energy but also for compensating the low efficiency of fuel-cell battery especially when the vehicle starts. Long life duration of ultra capacitor is also useful for starter battery on delivery track. This paper presents a novel small electric vehicle which has only EDLC as the energy source.

The aim of making this vehicle is to take the advantage of the peculiar characteristic of large current charging in EDLC. The driving experiment and capacitance monitoring system are shown and our future plan on vehicle motion control using this characteristic will be discussed.

II. WHAT IS ELECTRICAL DOUBLE LAYER CAPACITOR (EDLC)

A. Principal of electrical double layer (EDL)

The phenomenon of EDL was discovered by Helmholz in 1879 [1]. The basic structure of EDLC is shown in Fig.1.

EDL is composed of the thin monomolecular layer and the diffusion zone outside. These two layers are called EDL collectively.

EDLC consists of plural capacitor cells, and the maximum voltage is determined by electrical dissociation voltage endurance of the electrolyte. The electrolyte used in our EDLC module is the special ionized liquid with high ionized conduction. It realizes the high ion conduction and thermal tolerance, so it suits to the demanding applications such as automobiles.

An EDLC module has many capacitor cells. Therefore, repetition of charging/discharging and the variation among cell voltages cause serious degradation of capacitor. To overcome this problem, EDLC has a small electronic circuit which equalizes the voltage among cells [1].

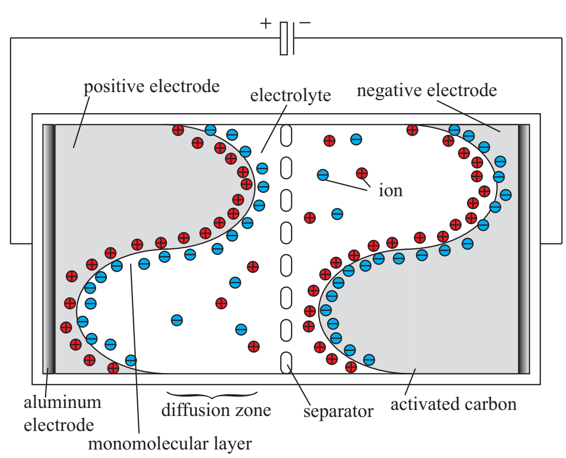

Fig. 1. Basic structure of EDL

B. Comparison with other secondary batteries

Fig.2 shows the comparison of EDLC parameters with other secondary batteries.

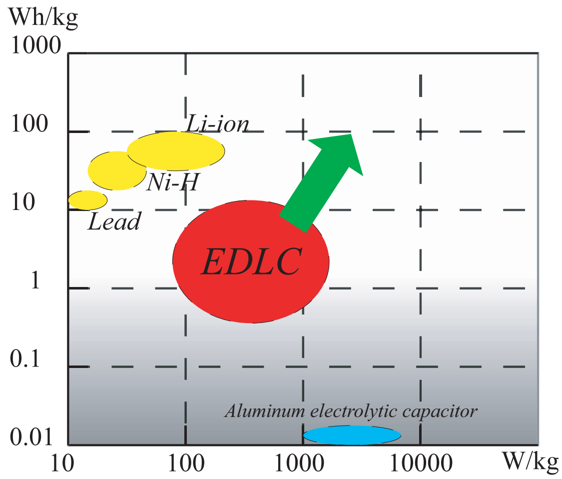

Fig. 2. Comparison with other secondary batteries

At the present day the EDLC's energy density is still small, but it has been increasing drastically these years. The advantages are that power density is 6.5 times as large as other devices and cycle life is semi permanent. These characteristics enable fast charging and make an electric vehicle suitable for experiments of motion control, where lots of experiments are needed in the same condition in short experimental time.

C. Characteristics of EDLC

Our EDLC modules were given by Nisshinbo and Japan Radio Company. The module has the special voltage equalization circuit. It prevents voltage variation among capacitor cells charging and stretches the capacitor's life expectancy. Table I indicates the specification of EDLC module.

TABLE I
Specification of EDLC module

Voltage	100V
Capacitance	26.7F
Internal resistance	80m Ω
Mass	12.4kg
Volume	287 × 260 × 161mm
Self discharging current	16.8mA

D. Capacitance monitoring system

It is recently that EDLCs are used in many ways, so it is the problem how to keep the reliability. Over voltage caused by charging or regenerating disgraces EDLC and decreases its capacitance. Consequently capacitance monitoring system is thought to be very useful. The calculation of capacitance is given in (1).

$$C(t) = \frac{Q(t)}{V(t) - R * I(t)} \tag{1}$$

Where Q is the electric charge accumulated in EDLC and given in (2).

$$Q(t) = Q_0(t) - \int_0^t I(t)dt \tag{2}$$

For using Eq(1), internal resistance have to be measured. Fig.??,?? shows the experimental result of constant current discharging. Voltage drops in constant current discharging are 0.4V in 5A and 1.6V in 20A. So the internal resistance is calculated as 80mΩ.

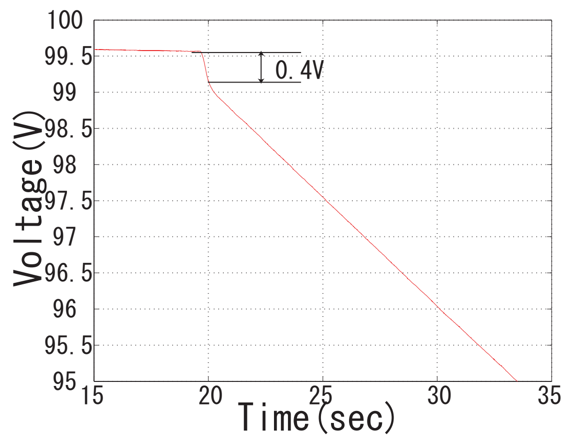

Fig. 3. 5A discharging

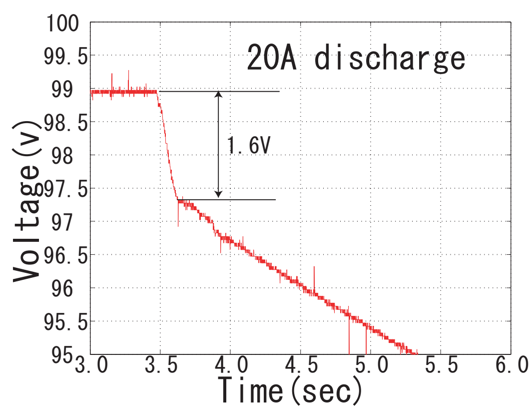

Fig. 4. 20A discharging

Fig.5 shows the calculation of capacitance using the driving experiment data. Capacitance has voltage relativity about 15%. This phenomenon is called "voltage relativity of EDLC", Fig.6 shows that the line is not linear but has some curves. This phenomenon is thouth to be one of the peculiar characteristic of EDLC and is under investigation. Nevertheless we think capacitance monitoring system work well as long as knowing the precise capacitance transition in advance.

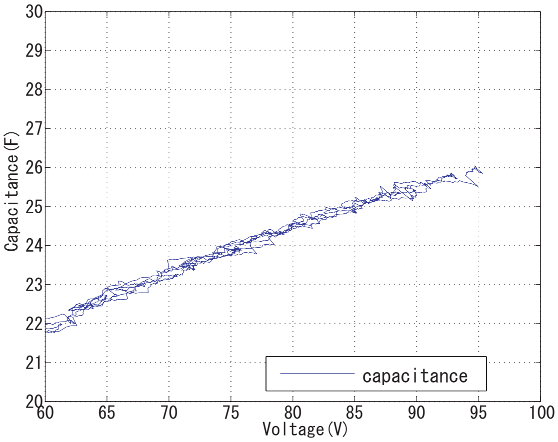

Fig. 5. Transition of capacitance

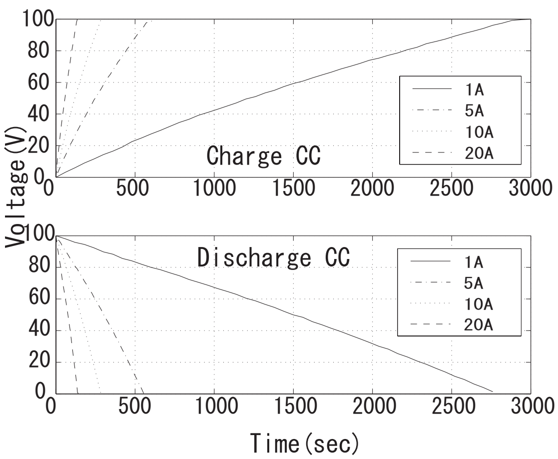

Fig. 6. Charge/discharge characteristics

III. VEHICLE SYSTEM

A. Specifications

Small vehicle named COMS is a one-seater vehicle made by Toyota Auto Body Co., Ltd. Fig.7 shows its outlook. These small electric vehicles are often used in delivery service because it saves space and is easy to drive. Drive train consists of batteries, inverters and PS motors. In detail, see Table II.

As the motors are very small, two motors are installed in rear wheels. This makes it possible to drive each motor independently, which will realize novel motion control of vehicle dynamics. For example, control with independent wheel torque control [2], yaw-moment stabilizing control using yaw-moment observer [3] can be investigated. Self-aligning torque estimation [4] and cornering stiffness estimation [5] are also important research subjects.

We explain some of these control techniques in more details in a following section.

B. Driving System

Existing inverter does not suit as the experimental vehicle, we are going to mount the new specification inverter.

Fig. 7. COMS

TABLE II
DRIVE TRAIN

Motor	
Category	PSM
Phase/Pole	3/12
Rating power/Max	0.29kW/2kW
Max torque	100Nm
Max speed	50km/h
Inverter	
Hardware	Transitor inverter
Control method	PWM vector control

Vehicle system is shown in Fig.8. LINUX PC calculates the command torque to the inverter from the velocity of each tire, rudder angle of steering wheel, acceleration and yaw rate information. The sampling time is 1 msec.

The vehicle status is showed in Fig.9. There are three statuses: when the inverter is started I/O check and voltage check are executed. It is "Stop mode". Then 3-phase current, temperature, vehicle velocity, torque command, hole sensor are confirmed, and on turning ignition switch the vehicle status transit to the "waiting mode". Pressing the break pedal and turning the vehicle starting switch makes the vehicle status transit to the "Runing mode".

IV. INSTALLATION OF THE CAPACITOR AND DRIVING EXPERIMENTAL RESULT

Three EDLC modules (100V,75F) are installed in the rear space with old inverter and basic driving experiment was performed, the result is in Fig.10. Driving course is a track and it took about 20 seconds per lap. As the vehicle is accelerated, the current increases.

This experiment explains three notable typical points of capacitor.

At first, the voltage decreases with driving, so we can know the remaining energy level properly.

Secondly, the voltage level drastically rises about 3 or 4V because the internal resistance of EDLC apparently drops the voltage level. If the current becomes zero, it looks that the voltage level suddenly rises. Generally the resistance

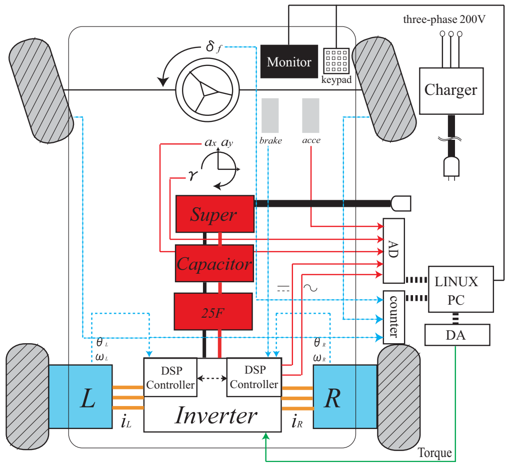

Fig. 8. Vehicle system

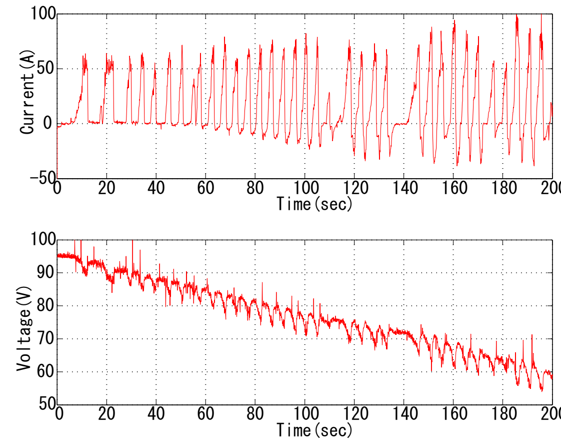

Fig. 10. Transition of capacitor voltage and current

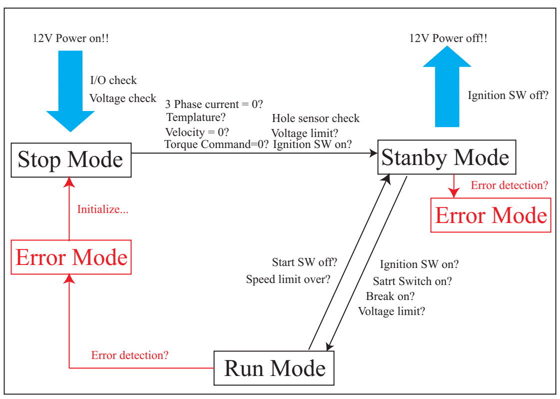

Fig. 9. Vehicle status

of EDLC is low(80mΩ), so the fluctuation of voltage does not have much effect on the system.

Lastly, the regenerating current is zero until the voltage reaches about 85V because the motor regenerative voltage is lower than the EDLC's one. Therefore the regenerating brake has an effect in the middle and low voltage region.

V. MOTION CONTROL USING ELECTRIC VEHICLE

A. Advantages of Motor Comparing to the Internal Combustion-engine

As we have pointed out, electric vehicle has the following four remarkable advantages:

- Motor's torque generation is 10-100 times faster than engine. This advantage enables us to realize high performance adhesion control, e.g., skid prevention and slip control.

- Motor's torque can be known easily by observing the motor current. This property can be used for road condition estimation.

- As a motor is compact and not so expensive if it is divided into four, it can be equipped for each wheel. This realizes high performance vehicle motion control.

- There is no difference between acceleration and deceleration control. Just by changing the direction of motor current, the vehicle can be decelerated.[6]

In the next section, we introduce and categorize the possible EV motion control techniques which can be realized taking these advantages.

B. Advantages of Motion Control on Electric Vehicle

- High performance braking control

Motor's controllability enables us a higher performance of braking control system.

1. Pure electric braking control in a whole speed range;
2. Hybrid ABS for HEV; combination of hydraulic brake and motor brake;
3. Direct control of driving force at each tire.

- Two-dimensional attitude control

The aim of this control is to find the optimal combination of controlling γ and β.

1. Decoupling control γ and β;
2. Higher performance coordination of active front steering and yaw control;
3. Vehicle dynamics control based on β estimation;
4. Dynamic driving force distribution considering side slip force and cooperation with suspension system under changing load.

- Road surface condition estimation

Using the motor characteristic of easy torque observation, we can estimate various kinds of parameters.

1. Estimation of gradient of μ-λ curve;
2. Estimation of the maximum friction coefficient;
3. Estimation of the optimal slip ratio to be used for SRC;
4. Higher performance yaw control based on the estimation of road surface condition.

In these control techniques, we discuss on Model Following Control(MFC), Direct Yaw-moment Control(DYC) and Normal Force Stabilization(NFS) in the next section.

1) Anti Skid Control based on MFC

In this section, anti slip/skid control using nominal model is proposed.

One-wheel model is described as the following equations.

$$M_w \dot{V}_w = F_m - F_{df} \quad (3)$$

$$M\dot{V} = F_{df} \quad (4)$$

Where M and M_w are the mass of the vehicle and wheel respectively, F_m is motor torque and F_{df} is driving force [6] [7].

Fig.11 explains this idea easily. A motor directly connects to a tire and the grand surface transmits the driving force to vehicle body.

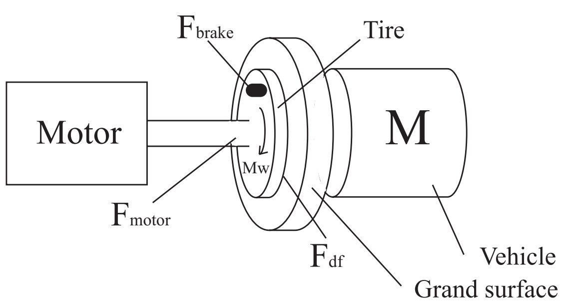

Fig. 11. Wheel model

If the road-surface condition is changed and becomes low during acceleration, driving-force would be sharply decreased. The rapid decrease of driving force will cause slip and make the vehicle motion unstable. In order to prevent such tire slipping, we can design the feedback control to reduce the driver's torque. This control strategy, called model following control (MFC) [6], demonstrates that the motor control can change the mechanical characteristics. Fig.12 is the basic block diagram and simulation result of MFC. The rapid increase of tire speed is effectively suppressed.

MFC can prevent the tire slip and skid quickly and more accurately than internal combustion one. Furthermore motor can be distributed in each wheel, so minor slip/skid control can be realized.

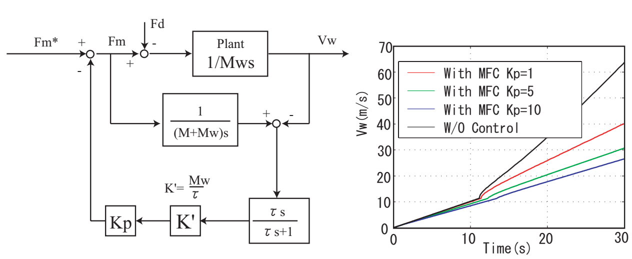

Fig. 12. MFC block(a) and simulation result(b)

2)Two-dimensional Attitude Control(DYC)

Distributed motors in each wheels means that each motors can drive independently. If left and right motors output different torques, yaw moment is generated on the center of the axle. Appropriate yaw moment stabilizes the vehicle behavior in dangerous turning. Yaw rate control of DYC method is shown in Fig.13 [8]. Yaw rate command is made from steering angle with first order delay. PI gains are determined by the Coefficient Diagram Method (CDM).

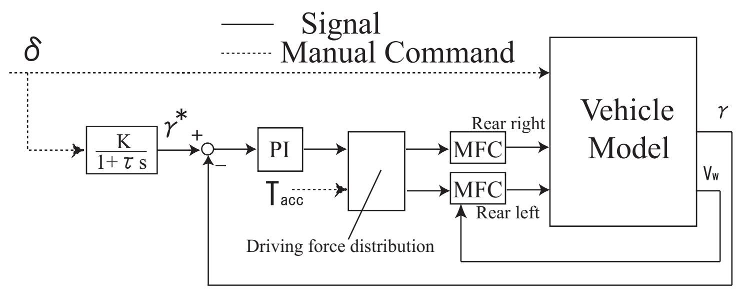

Fig. 13. Control system

Fig.14 is the simulation result of DYC. Yaw rate follows the command and the dangerous yaw rate increase is suppressed.

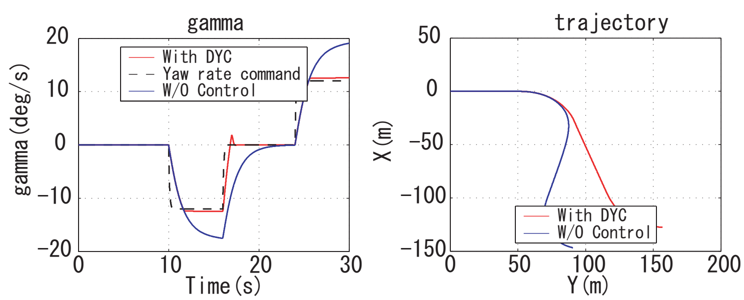

Fig. 14. Simulation result of DYC

3)Center of gravity (CG) control using normal force(NFS)

Lastly, the CG control using the acceleration sensor is introduced. With consideration of moment balance, the calculation of normal forces on the center of front and rear shaft (Fig.15) are given by Eq(5),(6).

$$F_{z-f} = \frac{m}{l_f + l_r}(l_r g + h a_x)) \quad (5)$$

$$F_{z-r} = \frac{m}{l_f + l_r}(l_f g - h a_x)) \quad (6)$$

The shift of CG $\Delta x, \Delta y$ is expressed as (8),(9)

$$-F_{z-f}(l_f - \Delta x) + F_{z-r}(l_r + \Delta x) = 0 \quad (7)$$

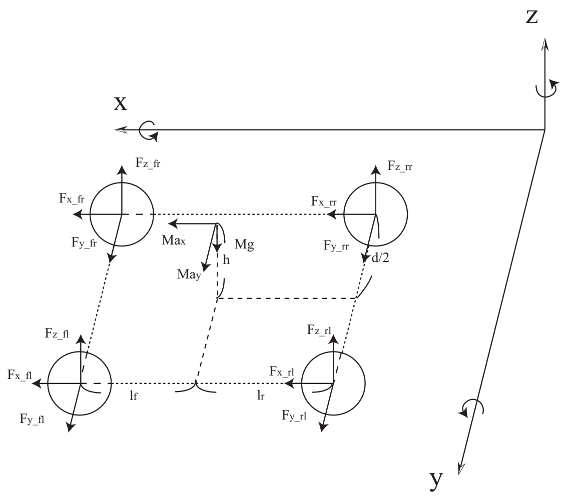

Fig. 15. Normal force on each tire

$$\Delta x = \frac{F_{z-f}l_f - F_{z-r}l_r}{F_{z-f}+F_{z-r}} = \frac{a_x}{g}h \quad (8)$$

In similar way,

$$\Delta y = \frac{a_y}{g}h \quad (9)$$

To suppress $\Delta x, \Delta y$ differential torque is commanded on each motor. The simulation result in right turning is shown in Fig.16. Shift of CG in lateral direction is efficiently suppressed by the differential torque.

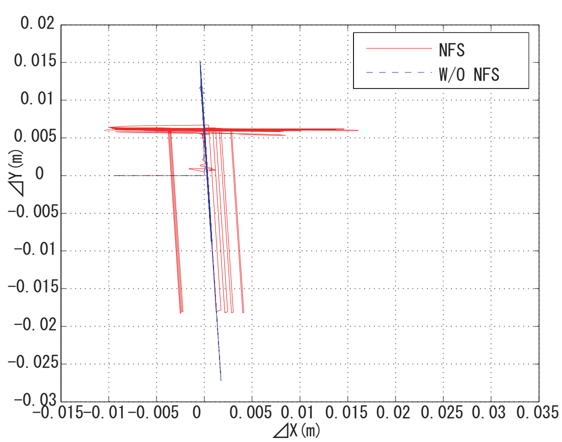

Fig. 16. Simulation result of CG controlling

VI. CONCLUSION

Manufacturing and driving experiment of small electric vehicle were conducted with EDLC module as the energy source. It was verified that charging time of EDLC is much shorter than lead acid batteries. Coming of an ubiquitous society, the role of power sources would be more important part. Based on the fact, we note the EDLC whose energy density drastically increases and proposed the novel usage of taking the EDLC as the power source of electric vehicle. At the last section, we listed up various future techniques to be done using this vehicle. Now, we are changing the inverter to the new specification one which is made to suit to EDLC module(allowance of low voltage region) and to vehicle motion experiments(short time delay and independent torque command to the right and the left motor), in the conference we are going to show you the videos of driving.

References

[1] Michio Okamura, Electrical double layered capacitor and storage system (in Japanese), pp.25-31, Nikkan-Kogyo-Shimbunsya

[2] Motoki Shino, Masao Nagai, "Independent wheel torque control of small-scale electric vehicle for handling and stability improvement", JSAE Review, Vol.24, pp.449-456, 2003

[3] Hiroshi Fujimoto, Takeo Saito, Toshihiko Noguchi, "Yaw-moment stabilizing control of small electric vehicle", AMC2004-Kawasaki, pp.35-40, 2004

[4] Daisuke Sekiguchi, Toshiyuki Murakami, "Vehicle steering assist by estimated self aligning torque in skid condition", AMC2004-Kawasaki, pp.269-273, 2004

[5] Akio Tsumasaka, Hiroshi Fujimoto, Toshiyuki Noguchi, "Cornering stiffness estimation of electric vehicle based on yaw-moment observer (in Japanese)", National Convention Record IEE of Japan -Industry Applications Society-, pp.II 551-552, 1987

[6] Yoichi Hori, "Future Vehicle driven by Electricity and Control-Research on Four Wheel Motored "UOT Electric March II", IEEE Transaction on Industrial Electronics, Vol.51, No.5, October 2004

[7] Shinichiro Sakai et al., "Novel skid detection method without vehicle chassis speed for electric vehicle, JSAE Review (Elsevier Science)", Vol.21, No.4, pp.504, 2000

[8] Masato Abe, Vehicle dynamics and control (in Japanese), Sankaido, 1992