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Vehicle Stabilizing Control Using Small EV Powered only by Ultra Capacitor

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Abstract— This paper presents the novel electric vehicle powered only by "Electrical Double Layer Capacitors (EDLC)" and the vehicle motion control using this vehicle. This vehicle provides easy experiment of electric vehicle motion control, since capacitor has the peculiar characteristic of large current charging. In this paper, the driving experimental data are shown first and capacitance monitoring system is proposed in the second section. The development of "Capacitor COMS" (C-COMS) and the vehicle control system will be shown in the third section. In the last section, various kinds of vehicle motion controls utilizing advantages of electric motor will be listed up and the simulation result of normal force stabilizing control is given.

I. INTRODUCTION

EDLC, whose energy density has drastically increased, is drawing much attention. EDLC has a lot of advantages as following [1].

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

Additionally, if we use EDLC's voltage from 100V to 30V, by a simple calculation of (1), we can know that more than 90% of charged whole energy of ELDC can be used.

$$\eta = \frac{\frac{1}{2}C(100^2 - 30^2)}{\frac{1}{2}C(100^2)} = 0.91 \qquad (1)$$

Capacitors have been used as backup batteries of mobile PC's, printers, UPS's, etc. In the field of automobile, some fuel-cell (hybrid) vehicles used 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 EDLC is also useful for starter battery of delivery track.

The aim of making the capacitor vehicle in our laboratory is to take the advantage of the peculiar characteristic of large current charging of EDLC. In the following section, the driving experimental result and capacitance monitoring system are shown. The development of C-COMS and the vehicle control system are described in the third section. In the last section, the vehicle motion controls utilizing advantages of electric motor are considered and the basic simulation result of normal force stabilizing control will be given.

II. APPLICATION OF EDLC AS THE POWER SOURCE OF ELECTRIC VEHICLE

A. Driving Experimental Result

EDLC modules (100V, 75F) are installed on the vehicle and basic driving experiment was performed. The result is shown in Fig.1. Driving course is a circle track and it took about 20 seconds per lap.

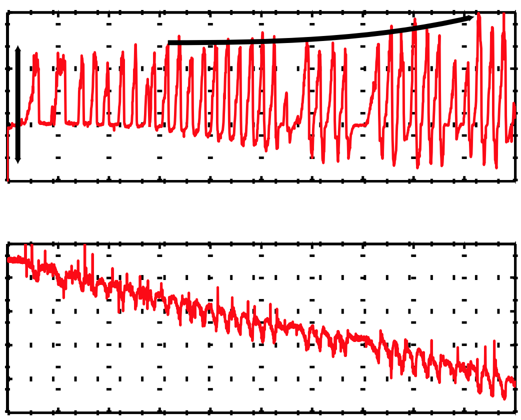


Fig. 1. Transition of capacitor voltage and current

This experiment shows several notable typical characteristics of capacitor.

At first, the voltage decreases with driving, and we can know the remaining energy level very easily.

Secondly, the terminal voltage clearly rises about 3 or 4V when the current become zero because of existence of the internal resistance of EDLC. Generally as the resistance of EDLC is low (80mΩ), the fluctuation of voltage does not have much effect on the system.

Thirdly, current increases in low voltage region. It is because the current compensates the voltage decrease. In this region, maximum speed is suppressed. Application of field weakening method will be one of the solutions to solve the problem.

Lastly, the regenerating current is zero until the voltage reaches about 85V because the over voltage from the regenerating current may damage ELDC module. Therefore the regenerating brake is effective in the middle and low voltage regions.

B. Capacitance Monitoring System

As it is quite recent when EDLCs have become used widely, it is the problem how to keep reliability. Over voltage caused by charging or regenerating damages EDLC and decreases its capacitance. Consequently capacitance monitoring system is very useful. Capacitance can be calculated by (2).

$$C(t) = \frac{Q(t)}{V(t) - R * I(t)} \tag{2}$$

Where Q is the electric charge accumulated in EDLC and is given by (3).

$$Q(t) = Q_0(t) - \int_0^t I(t)dt \tag{3}$$

Fig.2 shows the calculation result of capacitance using the driving experiment data (Fig.1). Capacitance has voltage dependence about 15%. This phenomenon is called "voltage dependence of EDLC". Fig.3 shows that the line is not linear but has some curve. This phenomenon is one of the peculiar characteristics of EDLC and is still under investigation.

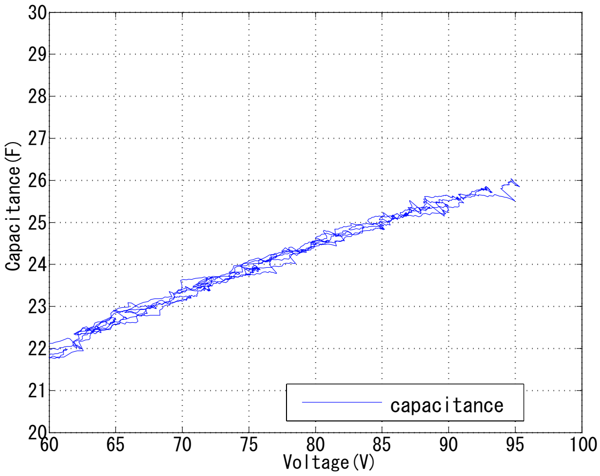


Fig. 2. Voltage dependence of ELDC

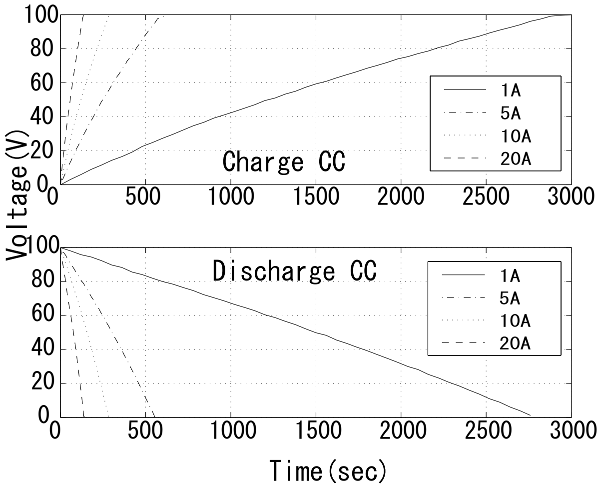


Fig. 3. Charge/discharge characteristics

III. Vehicle Control System

A. Vehicle Specifications

Our small vehicle named C-COMS is a one-seater vehicle with two in-wheel motors. Fig.4 shows its outlook. Drive train consists of batteries, inverters and permanent magnet synchronous motors. Table I shows its details.

Fig. 4. Capacitor COMS

The original inverter could not give the torque command to each motor independently and it has about 300 msec time lag from the acceleration command to the motor. Therefore we designed an inverter which can command torque independently and has little time lag to 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 installed. Self-aligning torque estimation [4] and cornering stiffness estimation [5] are also important research subjects.

B. Development of C-COMS

We developed following four new components which the original electric vehicle did not have.

TABLE I
Drive train

Electric 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

- Upper level PC for generating torque command and storing experimental data
- EDLC box and newly designed inverter mounting.
- Speed detector using PIC (Peripheral Interface Controller: a kind of micro computer)
- Steering encoder, acceleration/gyro sensor mounting.

At first, upper level PC is developed using PC104 standard embedded PC module. The merit of using this standard is that this PC is very small and has high extendability. Fig.5 shows the box, which consists of CPU boards, DC/DC converter, 12V fun, USB hub and several connectors. AD board reads in the acceleration command and calculates the required torque command also considering various sensors' information. Sensors' information and state variables are logged and stored in 2.5 inch hard disk drive.

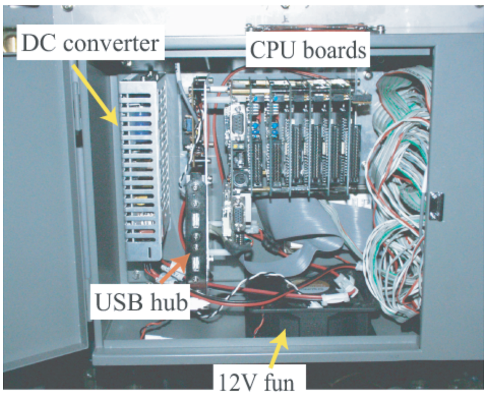


Fig. 5. Upper PC BOX

Secondly, EDLC box is manufactured for installing the EDLC modules. 21 EDLC modules (7 series $\times$ 3) are installed in this vehicle (Fig.6).

Thirdly, speed detector from the magnet sensor pulses is developed using PIC. In-wheel motors have magnet speed detector as shown in Fig.7. Three pulses are outputted together with 120(deg) phase lag each. We used PIC, which is very small (8 pin DIP) and inexpensive, for processing the three phase pulses conversion (Fig.8). It converts the three pulse signal into the speed pulse and the rotational direction signal.

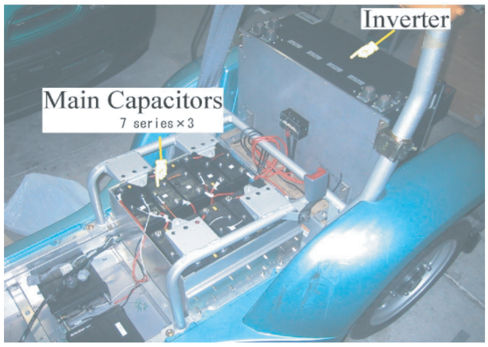


Fig. 6. Capacitor box and inverter

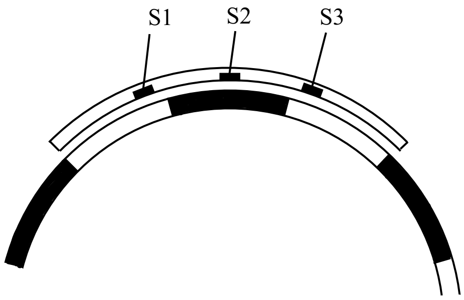


Fig. 7. Magnet sensor structure

Lastly, steering encoder and acceleration/gyro sensors are installed. These sensors' information is used for command torque generation.

C. Driving and Power System

LINUX PC calculates the torque command to the inverter using information of velocity of each tire, rudder angle of steering wheel, acceleration and yaw rate. Vehicle control system is shown in Fig.10. The sampling time is 1 msec.

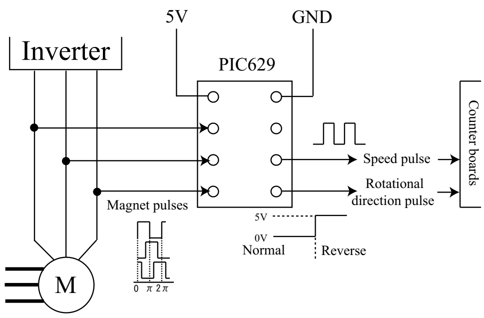
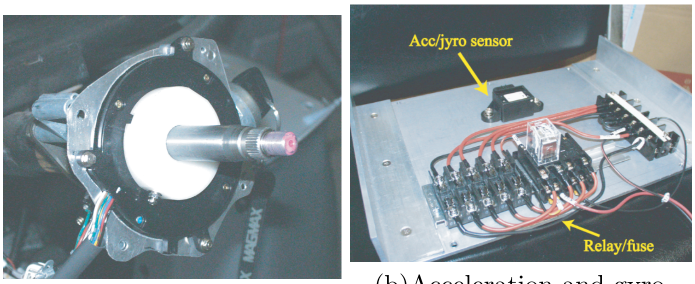


Fig. 8. 3 phase signal conversion using PIC



(a)Steering sensor mounting (b)Acceleration and gyro sensors mounting

Fig. 9. Installation of steering and acceleration/gyro sensors

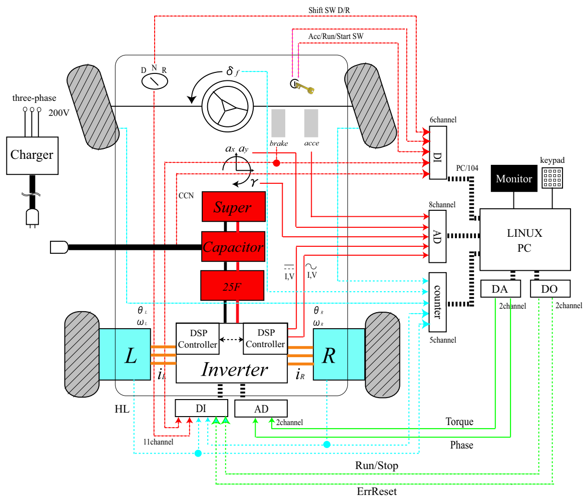


Fig. 10. Configuration of vehicle control system

IV. MOTION CONTROL USING ELECTRIC VEHICLE

A. *Advantages of Electric Motor Comparing to the Internal Combustion-Engine*

As we pointed out, electric vehicle has the following four remarkable advantages [6]:

- Electric 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.

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

- As an electric 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.

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

B. *Advanced Motion Controls Realized by Electric Vehicle*

Here we consider and list up the vehicle motion controls as follows.

- High performance braking control [6] [7]

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 [2] [3] [6]

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

1. Decoupling control of 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 [6]

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 (Slip Ration Control);
4. Higher performance yaw control based on the estimation of road surface condition.

In the next section we propose a novel control method "Normal Force Stabilization (NFS)".

C. *Normal Force Stabilizing Control using Acceleration Information*

C.1 Effectiveness of NFS

Among various two dimensional vehicle motion controls, γ and β controls are often proposed. Newly proposing NFS control method consider the vehicle rolling stability, too. The normal forces on each tire have big influence on vehicle rolling. In particular, normal force N relates to driving force F_d ($F_d = \mu \times N$). Sudden decrease of normal force causes tire slip, which makes whole vehicle motion unstable.

First, we calculate the normal force on each tire considering moment balance. Next, the instability index Δ is defined and the differential torque is commanded on each motor to suppress Δ.

C.2 Calculation of normal force and the instability index

Based on the consideration of moment balance, the normal forces on the center of front and rear shaft (Fig.11) are given by Eqs. (4) and (5).

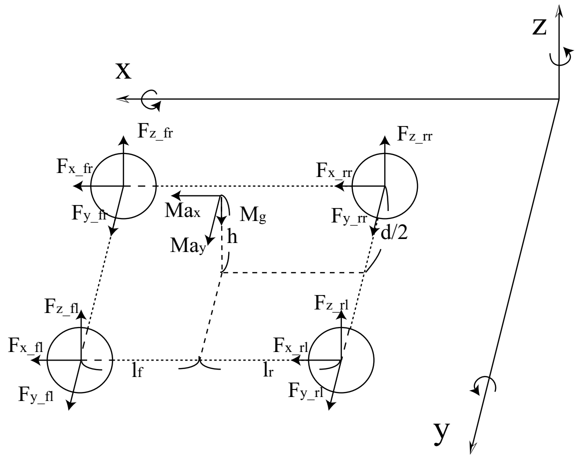


Fig. 11. Normal force on each tire

$$F_{z-f} = \frac{m}{l_f + l_r}(l_r g + h a_x) \tag{4}$$

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

Defining Δx, Δy (Δ), the normal force instability indices, the momentum balance equation in longitudinal direction is expressed by (6) [8].

$$-F_{z-f}(l_f - \Delta x) + F_{z-r}(l_r + \Delta x) = 0 \tag{6}$$

Δx, the index in x-direction is given by

$$\begin{aligned} \Delta x &= \frac{F_{z-f} l_f - F_{z-r} l_r}{F_{z-f} + F_{z-r}} \\ &= \frac{a_x}{g} h \end{aligned} \tag{7}$$

In a similar way,

$$\Delta y = \frac{a_y}{g} h \tag{8}$$

The index Δ is proportional to the acceleration. To suppress Δy, differential torque ΔF should be commanded on each motor. The Fig.12 shows the block diagram of this control method.

C.3 Simulation result

The simulation result in right turning is shown in Fig.13. Normal force instability index in lateral direction Δy is efficiently suppressed by the differential torque.

In actual experiment, acceleration information contain much noise, we need to eliminate noise with low pass filter.

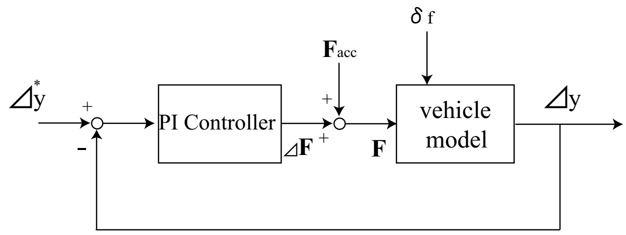


Fig. 12. Control diagram of NFS

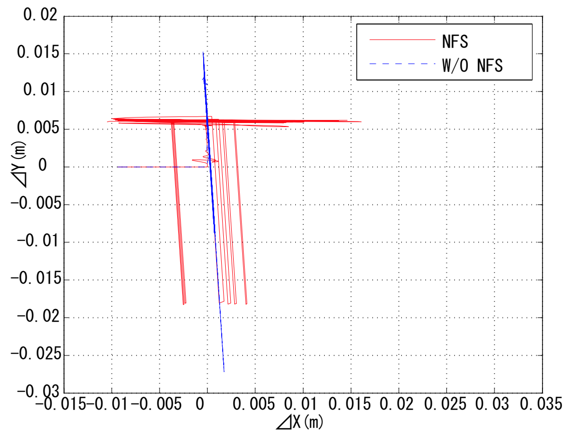


Fig. 13. Suppression of normal force instability index

V. CONCLUSION

Small electric vehicle with EDLC modules as the energy source is introduced and the advantages of such capacitor vehicle are shown by using the driving data. Next the capacitance monitoring system was proposed and detailed development of some components of C-COMS is mentioned. In the last section, the instability index of NFS control method is proposed and the simulation result of suppressing the index shows the effectiveness of NFS.

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