Normal Force Stabilizing Control Using Small EV Powered only by Electric Double Layer Capacitor

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This paper has two topics. The first one is development of novel electric vehicle (EV) powered only by "Electrical Double Layer Capacitor (EDLC)". The second one is normal force stabilizing (NFS) vehicle motion control using this experimental vehicle. The vehicle provides us useful experimental environment of EV’s motion control, since EDLC power system can shorten charging time. Only 30 seconds-charging enables us 20 minutes driving experiments. The development of small EV and the vehicle control system are shown. Novel vehicle stabilizing control in rolling motion using differential torque is proposed. Normal force has strong connectivity with driving force and its sudden decrease causes tire slip, which makes the whole vehicle motion unstable. The simulation and experimental results are shown and the effectiveness of proposed method is discussed.

Keywords: Light Vehicles, On-Board Energy Storage System, Double Layer Capacitor, Vehicle Motion Control

1. INTRODUCTION

Electrical double layer capacitor (EDLC), whose energy density has drastically increased, is drawing much attention. EDLC has several advantages as following.

1. It can be charged and discharged very quickly without heat generation because it is not based on chemical reaction.
2. Capacitor’s voltage level tells us the remaining energy level precisely.
3. Capacitor is very tough to endure the repetitions of charging and discharging.
4. Capacitor is environmental friendly because it does not use heavy metals.

Capacitors have been used as backup batteries of mobile PC’s, printers, UPS’s, etc. In the field of automobile, some fuel-cell and hybrid vehicles use capacitors not only for absorbing the regenerated energy but also for compensating the low efficiency of fuel-cell battery and secondary battery [1]. Long life duration of EDLC is also useful for starter battery of vehicles.

The purpose of making the capacitor vehicle is to develop the useful experimental environment of vehicle motion control taking the advantage of peculiar characteristic of large current charging. In the following section, the development of small EV “Capacitor COMS (C-COMS; Fig. 1)” and the vehicle control system are described. In the third section, the vehicle normal force stabilizing (NFS) control method is also proposed. Normal force has strong connectivity with driving force and its sudden decrease causes tire slip, which makes the whole vehicle motion unstable. Basic simulation and experimental results of NFS control are given in the forth section.

2. DEVELOPMENT OF SMALL ELECTRIC VEHICLE POWERED ONLY BY EDLC

EDLC modules (105V, 85F) are installed on the vehicle.

2.1 Merits of EDLC Application for EV

EDLC application for EV has following advantages
which secondary batteries do not have.

As EDLC is not based on chemical reaction and its internal resistance is small theoretically, large current charging is possible. EDLC is also more than 10 times as durable as for repetition of charging and discharging. In addition, EDLC voltage level tells us remaining energy level very precisely against that estimation of energy level on secondary battery is very difficult. Only 30 seconds-charging realizes 20 minutes driving in our system.

We adopted the system that EDLC is directly connected to inverter. The advantages of this system are effective space utilization and high energy efficiency compared to utilizing DC-DC converter. Fig. 2 shows voltage and current data of driving experiment. The figures show that increase of the current compensates decrease of the voltage in the low voltage region. Minus current indicates regenerative current.

Table 1 shows the comparison of EDLC parameters with other secondary batteries [2][3].

Table 1 Comparison with other secondary batteries

|            | Energy density | Power density | Cycle |
|------------|----------------|---------------|-------|
|            | Wh/kg          | Wh/l          | W/kg  |
| Lead       | 35             | 80            | 200   | 500   |
| NiMH       | 65             | 155           | 200   | 1000  |
| Li-ion     | 110            | 160           | 200   | 1000  |
| EDLC*      | 5.1            | 6.2           | 2420  | 100,000 |

*Nisshinbo 3V cell

Although the EDLC’s energy density is very small, the power density is more than 20 times as large as other devices and cycle life is more than 10 times. These characteristics enable fast charging and make an EV suitable for vehicle’s experiment, where lots of experiments are needed in the same condition in short experimental time.

This system can be applied to AGV (Automatic Guide Vehicle) or AGF (Automatic Guide Forklift) whose trajectory is fixed and required repetitive short-term use.

2.2 EDLC Specification

Table 2 shows the specification of EDLC module installed in C-COMS. A Module has 5 cells and maximum voltage is 3.0V. 21 EDLC modules (7 series × 3) are installed on the vehicle.

Table 2 Specification of EDLC module

|                |         |         |
|----------------|---------|---------|
| Voltage        | 15V     |         |
| Capacitance    | 200F    |         |
| Energy density | 3.4Wh/kg|         |
| Power density  | 4.0W/kg |         |
| Internal resistance | 8.9mΩ | |
| Mass           | 1.9kg   |         |
| Volume         | 155mmx66mmx154mm | |
| Number of modules | 21     |         |

2.3 Vehicle Specification

Our small vehicle named C-COMS is a one-seater vehicle with two in-wheel motors. Drive train consists of two inverters and two permanent magnet synchronous motors. Table 3 shows its details.

The original inverter could not give torque command to each motor independently and it has about 300 msec time lag from the acceleration command to the motor. Therefore we designed a new inverter which can generate reference torque independently and has little time lag to realize novel motion control of vehicle dynamics. This inverter was developed with due consideration for the voltage change.

Table 3 Drive train of C-COMS

|                |         |         |
|----------------|---------|---------|
| Category       | PM SM   |         |
| Phase/Pole     | 3/12    |         |
| Rating Power/Max| 0.29kW/2kW |         |
| Max torque     | 100Nm   |         |
| Max speed      | 50km/h  |         |
| Control method | PWM vector control | |
| DC input       | 30V - 100V |         |
| SW frequency   | 20kHz   |         |

2.4 Development of Capacitor-COMS

Fig. 3 shows the vehicle control system.

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

- ECU (Electrical Control Unit) for generating reference torques and storing experimental data
- EDLC box and newly designed inverter
- Speed detector using PIC (Peripheral Interface Controller)
- Steering encoder, acceleration/gyro sensor
ECU was developed using PC104 standard embedded PC module. The merit of using this standard is that this PC is very small and has high extendibility. ECU consists of CPU boards, DC/DC converter, 2.5 inch hard disk drive, and a cooling fan. AD board reads the acceleration command and ECU calculates the required torque command. Sensors’ information and state variables are logged and stored in the HDD.

Speed detector from the magnet sensor pulses was developed using micro computers. In-wheel motors have magnet speed detector. Three pulses are output together with 120(deg) phase lag each. We used PIC (8 pin DIP), which is very small micro computer and inexpensive, for converting three phase pulses of magnet sensors to speed pulse and rotational direction signal.

Utilizing these advantages slip prevention control, road condition estimation, yaw rate control and other vehicle stabilizing control methods had been proposed. For example, control with independent wheel torque control [6], yaw-moment stabilizing control using yaw-moment observer [7] had been studied. Self-aligning torque estimation [8] and cornering stiffness estimation [9] are also important research subjects.

3.2 Normal Force Stabilizing Control

We will show that normal force on each tire can be calculated by using acceleration information. Considering of moment balance, displacement of hypothetical center of gravity (HCG) can be estimated by these normal forces. Here, hypothetical means that suspension system is not taken into account.

3.2.1 Difference with Other Conventional Rolling Control Method with Active Suspension System

Though active rolling controls using active suspension system are widely studied [10]-[12], we propose the novel rolling control method utilizing differential torque on each tire.

We focus on that normal force on each tire is calculated using acceleration information and it is possible to estimate displacement of HCG. The purpose of NFS is to control displacement of HCG with differential torque. We do not need extra space for mounting active suspension system and we can utilize the algorithm easily by updating the software.

3.2.2 Normal Force Calculation on Each Tire

Considering of moment balance, the normal forces on the center of front and rear shaft at acceleration (Fig. 4, 5) are given as

\[ F_{z-f} = \frac{M}{l_f + l_r} (l_f g - ha_r) \]  
\[ F_{z-r} = \frac{M}{l_f + l_r} (l_f g + ha_r) \]  

Fig. 4 Normal force on each tire

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Where \( M \) is vehicle weight, \( g \) acceleration of gravity, \( a_x \) and \( a_y \) vehicle longitudinal and lateral acceleration, \( h \) height of HCG from ground, \( l_f \) and \( l_r \) distance between HCG and front and rear shaft, \( d \) right and left tire distance, \( \delta_f \) steering angle.

\[
F_{z-f} = \frac{1}{2} \frac{M}{l_f + l_r} (l_f h a_x + \frac{h M a_x}{d})
\]
\[
F_{z-r} = \frac{1}{2} \frac{M}{l_f + l_r} (l_r h a_x - \frac{h M a_x}{d})
\]
\[
F_{x-r} = \frac{M}{2 l_f + l_r} (l_f g + h a_x + \frac{h M a_x}{d})
\]
\[
F_{x-r} = \frac{M}{2 l_f + l_r} (l_r g + h a_x - \frac{h M a_x}{d})
\]

Eqs. (3-a,b,c,d)

### 3.2.3 HCG Calculation

Defining \( \Delta x \), \( \Delta y \) as displacement of HCG (normal force instability indices), the momentum balance equation in longitudinal direction is expressed by Eq. (4).

\[
-F_{z-f} (l_f + \Delta x) + F_{z-r} (l_r - \Delta x) = 0
\]  

\( \Delta x \) is given as following equation.

\[
\Delta x = \frac{-F_{z-f} l_f + F_{z-r} l_r}{F_{z-f} + F_{z-r}}
\]

\[
= \frac{a_x}{g} h
\]  

In a similar way, \( \Delta y \) is given as

\[
\Delta y = \frac{a_y}{g} h
\]

Eqs. (5) and (6) indicate that indices \( \Delta x \) and \( \Delta y \) are proportional to acceleration. To suppress \( \Delta y \), differential torques are commanded on each motor. Fig. 6 shows the block diagram of this control method.

### 3.3 Simulation Results of NFS Control

The simulation results in right turning and sinusoidal steering input are shown in Fig. 7. In actual experiment, acceleration information contains much noise, we need to eliminate noise with low pass filter.

![Fig. 6 NFS control diagram](image)

![Fig. 7 Simulation results of NFS control](image)
results show the effectiveness of NFS control.

4. EXPERIMENTAL VERIFICATION OF NFS CONTROL

4.1 Experimental Condition
Experimental conditions is that driver turns the steering wheel as step and sinusoidal under constant velocity. Experimental terms are followings,
- Step steering input, $\Delta y'$ is zero
- Sinusoidal steering input, $\Delta y'$ is zero
- Step steering input, $\Delta y^*$ is generated from steering angle
- Sinusoidal steering input, $\Delta y^*$ is generated from steering angle

To know the basic vehicle behavior with differential torques, NFS control experiment is applied when $\Delta y'$ is zero. The experimental results of step and sinusoidal steering input are shown in Fig. 8. With the larger control gain $K_p$, the differential torques on right and left tires suppress $\Delta y'$ more effectively. These figures correspond to the simulation results in the previous section.

4.2 Experimental Results of NFS Control
In this section, four kinds of experimental results are shown mentioned above.

4.2.1 Experimental Results of NFS Control when $\Delta y^*$ is Zero

Following Eq. (7) using gain $K$, vehicle’s velocity $V$, $\Delta y^*$ is generated from steering angle and velocity

$$\Delta y^* = K \cdot V \cdot \delta_f$$  \hspace{1cm} (7)

Fig. 9 Experimental results when $\Delta y^*$ is generated from steering angle and velocity
“ride quality”, but also “vehicle active safety” in turning motion. Normal force has strong connectivity with driving force whose sudden decease would make vehicle motion unstable. NFS control method will be one of the solutions of vehicle safety and ride quality in turning motion.

5. CONCLUSION

In this paper, the development of experimental vehicle powered only by EDLC is introduced and novel vehicle stabilizing control method using lateral acceleration information is proposed. Short charging time realized by EDLC power system provides us useful experimental environment. The simulation and experimental results indicate the effectiveness of NFS control method. We do not need extra space for any hardware and we can utilize the algorithm only changing the software. Dangerous steering input is effectively suppressed and $\Delta V$ is controlled with reference variables. By controlling $\Delta V$, the novel vehicle active safety is realized in turning motion.

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BIOGRAPHIES

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