Application of Advanced Motion Control Techniques and the Prospect of Super Capacitors in Electric Vehicles

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Abstract— **With the advantages of high controllability of driven motors and high performance of novel electric energy storage devices, the control performance of electric vehicles can be improved dramatically. That has been demonstrated by the researches, which include 1)side slip angle estimation; 2)real-time smart speed pattern generator which realizes "easy driving" and "smooth driving" on driver's command; 3)cooperative control of the hydraulic braking and the motor regenerative braking, which can get higher stability performance and higher energy efficiency; 4)optimal and dynamical driving force distribution control; 5)novel electric vehicle powered only by electrical double layer capacitor and motion control used in this vehicle. "UOT March Ⅱ", "UOT Cadwell EV", "Capacitor COMS I" and "Capacitor COMS Ⅱ" are our experimental EVs for those mentioned researchers.**

Key Words : ***electric vehicle, motion control, side slip angle estimation, speed pattern, regenerative braking, super capacitor, force distribution control***

I. Introduction

Electric vehicles (EVs) will be major vehicles in the middle of the 21st century[1]. An outstanding advantage of EVs over traditional internal combustion engine vehicles (ICVs) is the controllability of the driven motors, which makes the EVs have the following merits for motion control[2].

1. Quick and accurate torque generation, for both accelerating and decelerating.
2. Motor can be attached to installed into each wheel.
3. Motor torque is easily comprehensible.

We mention our researchers on EVs as follows.

In chapter II, we discuss the method of side slip angle estimation, which is used for vehicle motion control. In chapter III, we show a real time smart speed pattern generator (RSSPG), which realizes "easy driving" and "smooth driving" on drivers command.

Chapter IV mentions a cooperative control method of hydraulic braking and motor regenerative braking, which can also get higher stability performance. Regenerative braking is commonly adopted in EVs for energy efficiency. Furthermore, the generated torque of electric motors can be controlled much more quickly and precisely than that of hydraulic actuator.

Chapter V introduces optimum force distribution control. Optimally and dynamically distributing traction forces of four driving motors will generate the yaw moment. It can be used for EV maneuverability improvement.

At last, in chapter VI, we introduce the development of a novel electric vehicle powered only by "electrical double layer capacitor (EDLC)". We call it "capacitor COMS".

Applying new kind of electric energy storage devices is also an attractive researching topic in EV development areas.

"UOT March Ⅱ", "UOT Cadwell EV", "Capacitor COMS I" and "Capacitor COMS Ⅱ" are our experimental EVs for those mentioned researchers.

We use two-wheel model, which is shown in Fig.1, for the proposed observer. State equation is expressed in Eq.1. Output equation is shown in Eq.2.

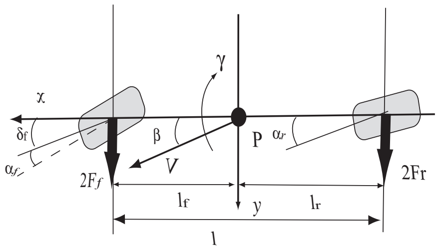


Fig. 1. Two-wheel model of vehicle motion

$$\dot{\boldsymbol{x}} = \boldsymbol{A}\boldsymbol{x} + \boldsymbol{B}\boldsymbol{u} \tag{1}$$

$$\boldsymbol{A} = \begin{bmatrix} \frac{-2(C_f+C_r)}{mv} & \frac{-2(l_fC_f-l_rC_r)}{mv^2} - 1 \\ \frac{-2(l_fC_f-l_rC_r)}{I} & \frac{-2(l_f^2C_f+l_r^2C_r)}{Iv} \end{bmatrix}$$

$$\boldsymbol{B} = \begin{bmatrix} \frac{2C_f}{mv} & 0 \\ \frac{2l_fC_f}{I} & \frac{1}{I} \end{bmatrix}, \quad \boldsymbol{x} = \begin{bmatrix} \beta \\ \gamma \end{bmatrix}, \quad \boldsymbol{u} = \begin{bmatrix} \delta_f \\ N \end{bmatrix}$$

$$\boldsymbol{y} = \boldsymbol{C}\boldsymbol{x} + \boldsymbol{D}\boldsymbol{u} \tag{2}$$

$$\boldsymbol{C} = \begin{bmatrix} 0 & 1 \\ va_{11} & v(a_{12}+1) \end{bmatrix}, \quad \boldsymbol{D} = \begin{bmatrix} 0 & 0 \\ vb_1 & 0 \end{bmatrix}, \quad \boldsymbol{y} = \begin{bmatrix} \gamma \\ a_y \end{bmatrix}$$

To estimate β, we use full order observer, which is shown in Fig.2.

$$\dot{\hat{\boldsymbol{x}}} = \boldsymbol{A}\hat{\boldsymbol{x}} + \boldsymbol{B}\boldsymbol{u} - \boldsymbol{K}(\hat{\boldsymbol{y}} - \boldsymbol{y}) \tag{3}$$

$$\hat{\boldsymbol{y}} = \boldsymbol{C}\hat{\boldsymbol{x}} + \boldsymbol{D}\boldsymbol{u} \tag{4}$$

where the K is observer matrix gain.

Based on consideration of pole assignment and robustness against cornering power, K is decided as

$$\boldsymbol{K} = \begin{bmatrix} \frac{\lambda_1\lambda_2}{C_f}\frac{(lf-lr)I}{2(lf^2+lr^2)+4lflr} - 1 & \frac{1}{v} \\ -\lambda_1 - \lambda_2 & \frac{m(lf^2+lr^2)}{(lf-lr)I} \end{bmatrix} \tag{5}$$

λ_1 and λ_2 are the assigned poles of the observer.

We performed four experiments by "UOT March II", which is shown in Fig.3.

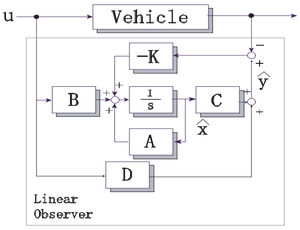


Fig. 2. Linear observer

Fig. 3. "UOT March II"

In order to test the robustness, we changed vehicle velocity, driver's input steering wheel angle δ and road type in experiments. Fig.4 is one of the experimental results, which demonstrates that the proposed observer is robust and even if velocity, steering angle and road condition is changed, the observer could still well estimate β[3].

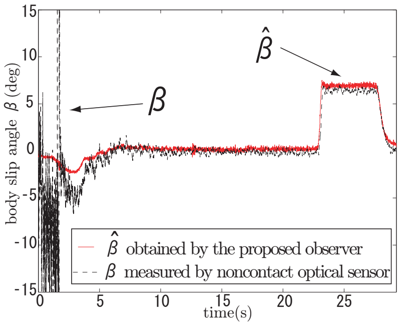
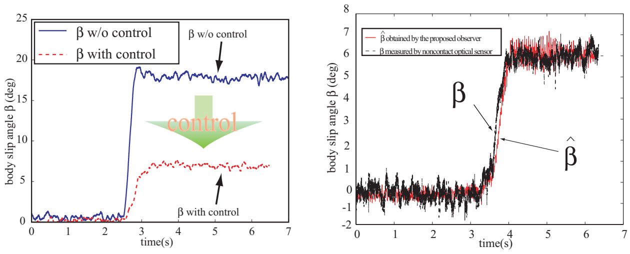


Fig. 4. Measured value and estimation of β

Next, we propose a new control method for 2-Dimensional control. We control β by yaw moment with PID controller. This method is known as DYC (Direct Yaw moment Control) in internal combustion engine vehicles (ICVs). However, the torque difference can be generated directly with in-wheel motors. We performed experiments by "UOT March II". The experimental results, which is shown in Fig.5, prove that our proposed method is good[4].

II. REAL TIME SMART SPEED PATTERN GENERATOR

In this chapter, we propose a novel motion control method for EVs based on real time SMART speed pattern generation (RSSPG). We especially consider the design of a speed pattern which can be generated in real time taking account of driver's command change. Three parameters of RSSPG can be determine arbitrarily and separately based on the optimal control theory, which improve the safety and ride comfort in ordinary traveling and emergency, and also enable flexible pattern generation.



(a) Comparisons (b) Estimation of β

Fig. 5. Experiment results about β control

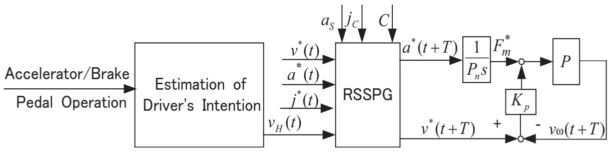


Fig. 6. Motion control of EVs using speed pattern

Fig.6 shows the block diagram of motion control of EVs using speed pattern, which consists of 3 parts: estimation of driver's intention based on the accelerator/brake pedal operation, generation of speed pattern, and motion control of vehicle utilizing generated speed pattern. This will enable to fill the gap of drivers's riving skill, and improve not only ride comfort but also safety by achieving two things as follows:

1. generation and application of speed pattern according to driver's intention of traveling.
2. smooth and speedy acceleration/deceleration.

The remaining part of Fig.6 shows the control system that is applied to implementation of the proposed speed pattern. To improve a tracking performance and disturbance robustness, this system contains feedforward acceleration and feedback of motor speed. This will enable to lessen the stress on the driver.

We had proposed the speed pattern based on SMART control design [5] to reduce jerk or the time derivative of acceleration which is often related to ride comfort[6]. However, there is the very important factor to consider in the application of speed pattern to Evs the change of driver's input occurs during mid-pattern, a new speed pattern must be recalculated in real time, which can be realized by our proposed RSSPG Fig.7 shows the flow chart of RSSPG

We assume that expected final speed input $v_H(t)$ can be changed in real time. Slope of jerk $6C_0(t)$ is determined based on jerk command $j(t)$, acceleration command $a(t)$, speed command $v(t)$, and expected final speed input $v_H(t)$ of time t, and jerk command $j(t+T)$, acceleration command $a(t+T)$, and speed command $v(t+T)$ of time $t+T$ are calculated as RSSPG outputs, where T is the sampling time.

The parameter C, or the changing rate of jerk, can be adjusted to fit accelerator/brake actions of human driver's

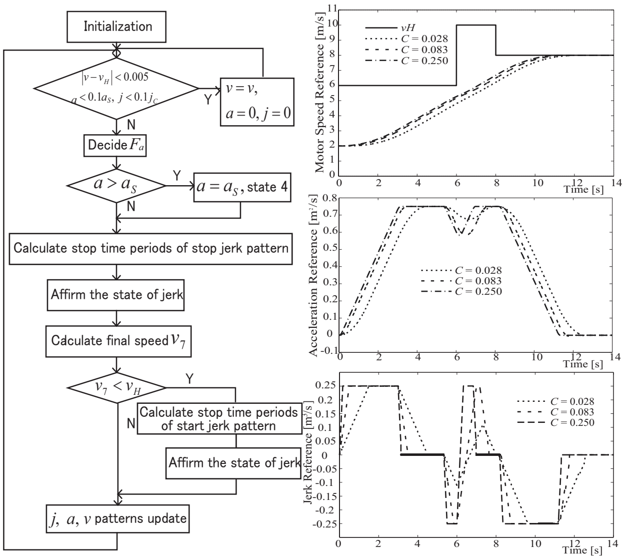


Fig. 7. Flow chart of RSSPG and speed, acceleration and jerk output pattern

with different driving styles or the favorite traveling style of passengers. For example, as shown in Fig.7, someone who wants acceleration feel, however, someone who wants slow acceleration. In addition, the simulation results in Fig.7 shows that a new speed pattern is really recalculated in real time, when the change of driver's control input $v_H(t)$ occurs during mid-pattern. The maximum safe acceleration a_S in accordance with road condition and the acceptable maximum jerk j_C to ride comfort are adjustable, too.

In the future, this algorithm needs to be improved and examined by real experiment.

III. ADVANCED HYBRID BRAKING SYSTEM

A. *Electric braking system cooperating with hydraulic actuator based on disturbance observer*

Almost all braking systems are made of hydraulic actuator.They have a long response delay, but they can generate sufficient braking torque[7][8].

Contrary, electric motor has quick and accurate output torque, and can be used both in traction and braking.

However, the power of electric motor is smaller, and it is impossible to generate sufficient braking torque only with electric motor.

Therefore, we propose a novel braking system using electric motor which compensates for hydraulic actuator. In this system, we use disturbance observer, regarding difference from command of hydraulic actuator as disturbance.

We show the block diagram of this system in Fig.8, where M is weight of vehicle body, M_ω is inertia of vehicle body, P_{hyd} is the model of hydraulic actuator, and P_{motor} is model of electric motor.

We assume the nominal model of vehicle body in adhesion condition, and obtained as equation(6).

$$P_n(s)=\frac{1}{(M+M_\omega)s} \tag{6}$$

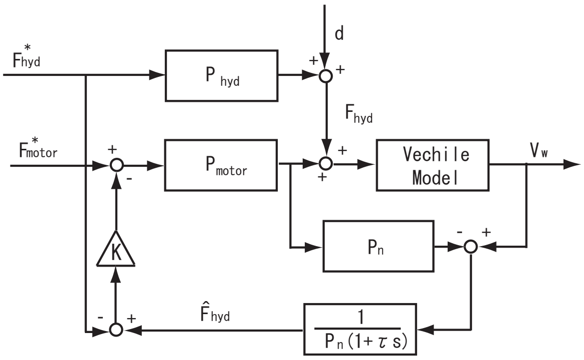
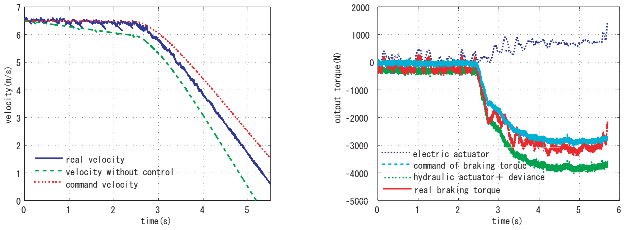


Fig. 8. Block diagram of braking system using vehicle nominal model

B. *Experimental results*

Experiments of braking system using electric motor which compensates for hydraulic actuator were carried out with "UOT March II". In experiments, we drove at constat velocity before we apply brake sharply on the asphalt road.

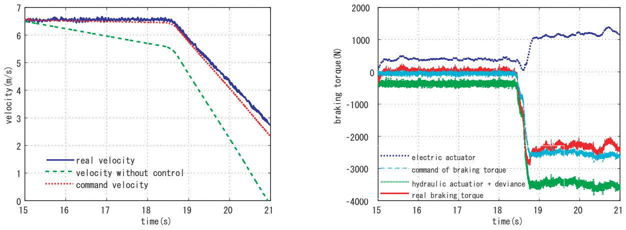
First, we show the experimental result using velocity sensor in Fig.9. In this condition, we need LPF which has large time constant because the differential signal of velocity sensor vibrates drastically. For that, we cannot effectively use the feature of electric motor.



(a) Velocity (b) Braking torque

Fig. 9. Experimental Result using velocity sensor

Next, we show the experimental result using acceleration sensor in Fig.10. In this experiment, both velocity and acceleration follow the command. As compared to system using velocity sensor, the vibration of input is reduced, and thus we can effectively use the feature of electric motor.



(a)Velocity (b)Braking torque

Fig. 10. Experimental Result using acceleration sensor

The experimental results verify the effectiveness of the proposed method.

IV. Dynamic optimum force distribution

Dynamic optimum force distribution control is one method used for controlling over actuated system, which is shown in Fig.11. In an over actuated system, the number of actuators n exceeds the number of control effectors m. There exit redundant control inputs which can be optimally chosen to control the state variables. And that control subjects to several constraint conditions.

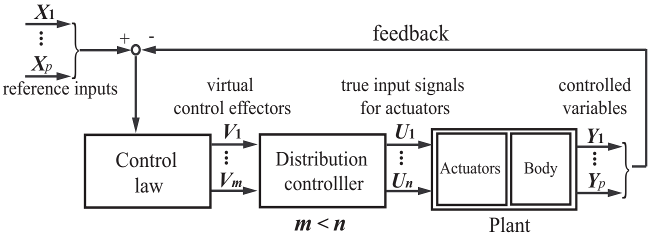


Fig. 11. Block diagram of over actuated system

For example, "UOT March II" has four in-wheel motors. For planar motion control, the controlled variables are yaw rate γ and/or vehicle body slip angle β. The control effectors which are calculated by higher level controller represent the forces F_Σ, yaw moment M_z, and/or adaptive steering angle Δ_f. Those values are required for control design. However, those control effectors can only generated through traction force control of EV motors. When redundant driving motors exit, force distribution control can be used to choose the most optimal control one.

Constrainted optimal control method is used for optimum force distribution. We design the control logic in two steps. First we calculate the control effectors, $V_1, ..., V_m$, by a higher level controller without considering the redundant driving motors. Second, with the calculated control effectors, we calculate the control inputs, $U_1, ..., U_n$, with considering the redundancy and constraints of optimal problem.

A. *Optimum traction force distribution for maneuverability improvement*

The block diagram of control system is shown in Fig.12. EV maneuverability improvement, which is the control objective, is realized by controlling EV to track the desired yaw rate. During that kind of control we test the proposed optimum traction force distribution control method.

In Fig.12, the feedforward controller is a P-controller. Feedback controller is a LQR regulator. Four motored wheels which are looked on as the control inputs for the control system can be controlled by the proposed method. Yaw rate γ is the control output[9][10].

B. *Experiment results*

In the experiments, the in wheel motored EV is controlled to turn a circle with constant radius. The friction coefficient is about 0.3 ∼ 0.4. During experiment, the steering angle is kept as possible as the same constant value. One of the experiment results is shown in Fig.13. It described that the yaw rate is controlled by the proposed method to well follows the reference one. And therefore the stability is enhanced and maneuverability is improved.

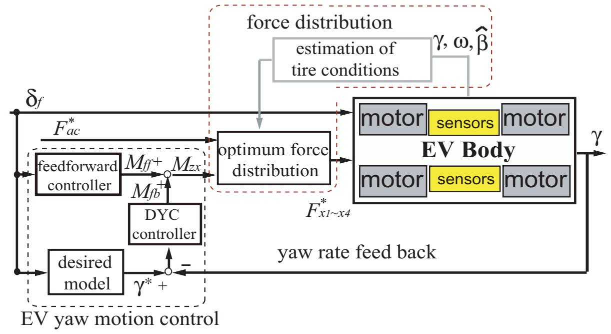


Fig. 12. Optimum force distribution integrated with yaw rate control for EV maneuverability improvement

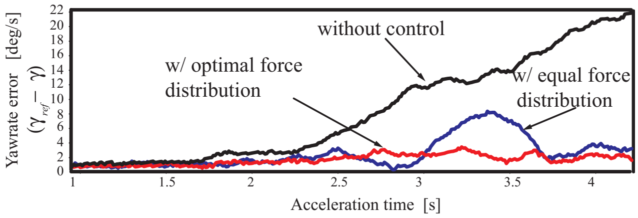


Fig. 13. Experiment result of optimum force distribution integrated with yaw rate control for EV maneuverability improvement

Dynamic optimum force distribution control has many merits when used for EV motion control.

1. Tire constraints can be taken into account;
2. Control reconfiguration can be performed when motor failure;
3. Motor can be controlled independently;
4. Less time of algorithm calculating;

In the future, this algorithm need to be updated further. And we have been researching other optimum distribution strategies based on the estimation of tire working conditions.

V. Small EV driven by ultra capacitor

This section has two topics. The first one is development of novel electric vehicle (Fig14) powered only by "electrical double layer capacitor (EDLC)". The second one is normal force stabilizing (NFS) vehicle motion control using this vehicle. This vehicle provides us useful experimental environment of electric vehicle motion control, since EDLC power system can shorten charging time. About 40 seconds charging enables us 20 minutes driving. The merit of EDLC application for EV and the vehicle control system are shown. Novel vehicle stabilizing control method using acceleration information 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 its effectiveness will be discussed.

A. Merit of EDLC application for EV

EDLC application for EV has following advantages which secondary batteries don't have.

1. Large current charging.
2. Voltage level tells us remaining energy level.
3. Durable for repetitive charge and discharge.
4. Environmentally friendly.

Theoretically EDLC is not based on chemical reaction and its internal resistance is small, large current charging is possible[11]. EDLC is also more than 100 times as durable as for repetition of charging and discharging. In addition, EDLC voltage level tells us remaining energy level very precisely against the estimation of energy level on secondary battery is very difficult. Using these advantages, we developed experimental vehicle named "Capacitor-COMS". Less than 1 minutes charging realizes 20 minutes driving.

Fig. 14. Overall view of C-COMS

Although the EDLC's energy density is very small, the power density is more than 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, where lots of experiments are needed in the same condition in short experimental time.

B. Normal force stabilizing (NFS) control using acceleration information

Considering of moment balance, the normal forces on the center of front and rear shaft (Eq.7 and 8) are shown in Fig.15 and 16.

B.1 Normal force stabilization control

$$F_{z-f} = \frac{m}{l_f + l_r}(l_r g + h a_x) \tag{7}$$

$$F_{z-r} = \frac{m}{l_f + l_r}(l_f g - h a_x) \tag{8}$$

Defining Δx, Δy (Δ), the normal force instability indices, the momentum balance equation in longitudinal direction is expressed by Eq.9[12].

$$-F_{z-f}(l_f - \Delta x) + F_{z-r}(l_r + \Delta x) = 0 \tag{9}$$

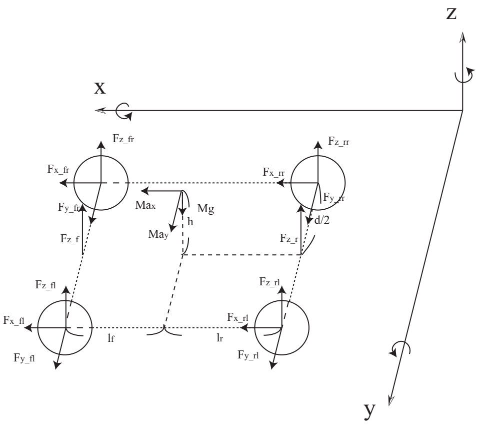


Fig. 15. Normal force on each tire

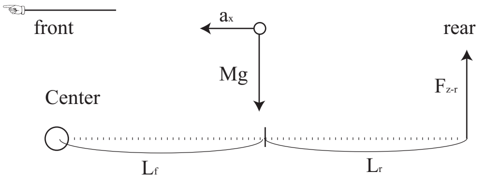


Fig. 16. Calculation of normal force

Δx, the index in x-direction is given by

$$\Delta x = \frac{F_{z-f} l_f - F_{z-r} l_r}{F_{z-f} + F_{z-r}} = \frac{a_x}{g} h \tag{10}$$

In a similar way,

$$\Delta y = \frac{a_y}{g} h \tag{11}$$

The indices Δ x,Δ y are proportional to the acceleration. To suppress these, differential torques are commanded on each motor. Fig. 17 shows the block diagram of this control method.

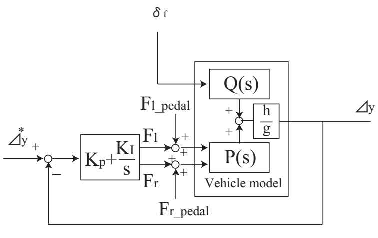
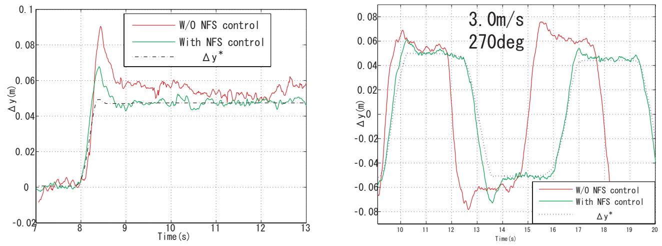


Fig. 17. NFS control diagram

C. Experimental results of NFS

Fig 18(a) and (b) are the cases that Δy^* is generated as following equation using gain K,vehicle speed V.

$$\Delta y^* = K V \delta_f \tag{12}$$



(a)Step steering input (b)Sinusoidal steering input

Fig. 18. Experimental results when Δy^* is generated from steering angle

Fine Δy suppression and following capability to Δy^* is verified with these results. Consequently, we can control and design the mobility of HCG in lateral direction, which is one of vehicle turning characteristics, by the differential torque of right and left motors. It is very important to control the mobility of HCG because it is related to not only “ 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.

In this section, 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. Dangerous steering input is effectively suppressed and is controlled with reference variables. By controlling, the novel vehicle active safety is realized in turning motion.

VI. Conclusion

This paper introduces the researches on novel EVs development and motion control by taking the advantages of high controllability of driven motors and novel electric energy storage devices.

We propose a robust side slip angle estiomation method. And we verify that method through the experiment. Based on the estimation of vehicle body side slip angle, a side slip control strategy is proposed. The effect of proposed method is also verified by experiments.

We also discuss a novel motion control method for EVs based on Real-time SMART Speed Pattern Generation using the optimal control theory. Three parameters of RSSPG can be determined arbitrarily and separately, which improves the safety and ride comfort in ordinary traveling and emergency, and also enables flexible pattern generation.

An advanced hybrid braking system is proposed. It is realized by cooperating electric braking systemwith hydraulic actuator based on disturbance observer. By utilizing electric motors for braking system, we can realize quicker and more precise braking system to compensate the slower response ability of hydraulic braking system in braking stability control. The experimental results verify the effectiveness of the proposed hybrid braking system.

Optimum force distribution control is introduced. Actuator redundancy is optimally used to avoid tire slip or lock and improve dynamic characteristics of EV, especially when EV drives in critical conditions. Experiment results indicate that the proposed force distribution method more greatly improve EV performance than the equal distribution one does.

The development of experimental vehicle powered only by EDLC is introduced and the novel vehicle stabilizing control method using lateral acceleration information is proposed. The simulation and experimental results indicate the effectiveness of NFS control method.

It becomes clear that electricity and control are the key solution of vehicles in future. These vehicles will by definition have electric motor driven-train and novel energy device, which that can present an opportunity to get higher control performance over traditional vehicles.

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