Paper

Motion Control of Electric Vehicles and Prospects of Supercapacitors

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Novel motion control techniques for electric vehicles (EVs) based on the quick torque generation in these vehicles have been developed at the Hori Laboratory. Since EVs are powered by electric motors, they have three major advantages: (1) motor torque generation is quick and accurate; (2) a motor can be attached to each wheel; and (3) motor torque can be estimated precisely. These advantages enable us to (1) easily realize high-performance antilock braking systems and traction control systems with minor feedback control of each wheel, (2) control chassis motion, e.g., direct yaw control; and (3) estimate road surface condition. We have developed test vehicles and confirmed the effectiveness of the proposed methods. Recently, we have manufactured small EVs that are powered only by supercapacitors. Supercapacitors have long operating life, have large current density, and are environmental friendly. Further, their energy level can be estimated from their terminal voltage. Since EVs powered by supercapacitors can run for more than 20 min by charging only for 30 s, recharging EVs will not be a major problem. In the future, EVs will be recharged via contactless power transfer.

Keywords : electric vehicle, motion control, adhesion control, slip angle estimation, super capacitors, contactless power transfer

1. Introduction

In the recent times, electric vehicles (EVs) have attracted considerable interest since they provide a solution to environmental and energy problems. With the improvement of motors and batteries, the driving performance of EVs has improved, and some EVs powered only by secondary batteries have already entered commercial markets.

From the viewpoint of electrical and control engineering, EVs are more advantageous than conventional internal combustion engine vehicles (ICVs). The advantages of EVs are summarized as follows: [(1)~(3)]

(1) The torque generation in EVs is very quick and accurate.
(2) The output torque of their motors can be easily estimated.
(3) A motor can be attached to each wheel of EVs.

We have studied the motion control techniques that help in increasing the efficiency of EVs by taking into consideration these advantages. In this paper, we present some novel motion control techniques developed at the Hori Laboratory.

Since the torque generation in EVs is quick, skidding can be easily prevented by reducing the torque. Further, the smooth torque control will assist the gearshift operations in manual transmission vehicles. In this paper, we present an improved method for the estimation of the vehicle sideslip angle β of EVs. This method is based on the advantages of EVs.

Limited energy storage and inefficient energy supply are critical problems faced by EVs; these problems have limited the widespread use of EVs. We have developed some EVs that are powered by electric double-layer capacitors (EDLCs) or the so-called supercapacitors. These supercapacitors have various advantages over conventional batteries, e.g., long operating life and large current density. It is expected that the development of EVs powered by supercapacitors will revolutionize the transportation system. In the last section of the document, we present our research on contactless power transfer systems, which we have just started.

Please refer to our previous review papers [(1)~(15)] for detailed explanations on motion control techniques from the technological viewpoint. In this paper, we skip basic formulae and equations that have been already introduced in the cited references.

2. Skid Prevention in EVs Based on Torque Reduction Characteristic of Electric Motors

EVs have one or more electric motors. In order to control the output torque according to the position of the accelerator pedal, controlled feedback (FB) current is fed to the driving motor. However, if the motor torque is controlled quickly and precisely, the tire speed will increase drastically when tire slip occurs. In order to maintain the adhesion between the tires and the road surface, it is necessary to decrease the motor torque quickly. In the conventional skid prevention controls developed by us, [(4)(5)] such slip controllers have been placed outside the current control system.

In this study, we modify the current control system. [(9)(10)] The required torque reduction when tire slip occurs can be determined by estimating the back EMF. In fact, the current control system is based on a combination of FB and feedforward (FF) current controls, as shown in Fig. 1.

The moment of inertia $J(\lambda)$ of all the rotating parts of an EV is given as a function of the slip ratio λ as follows:

$$J(\lambda) = J_{\omega} + r^2 M(1-\lambda) \quad \text{..............................(1)},$$

where J_{ω} is the moment of inertia of the tires, r is the tire radius, and M is the mass of the EV. λ varies between 0 and 1, indicating the slip condition; it approaches 1 when the probability of tire

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slipping is high. Therefore, $J(\lambda)$ decreases with increasing λ. From Fig. 1, the transfer function $G(s)$ from the voltage reference v^* to the real current of the motor, i, is expressed by

$$G(s) = \frac{i}{v^*} = \frac{1}{Ls + R + \dfrac{\varphi_f^{\,2}}{J(\lambda)s}} \qquad \text{.............................(2)}$$

where L and R are the inductance and resistance of the armature circuit, respectively, and ϕ_f is the torque/voltage coefficient of an equivalent dc motor. We use permanent magnet type synchronous motors and apply the control principle in Fig. 1 to the q-axis current component.

In Fig. 1, $G_n^{-1}(s)$ is the inverse transfer function of $G(s)$ with no slip, and is used for FF current controller. The value of $J(\lambda)$ when there is no tire slip (λ = 0) is given by $J_n = J_\omega + r^2 M$. Thus, we obtain

$$G_n^{-1}(s) = \frac{i^*}{v^*} = Ls + R + \frac{\varphi_f^{\,2}}{J_n s} \qquad \text{.............................. (3)}$$

As a result, the transfer function from i^* to i is given by

$$\frac{i}{i^*} = G(s)G_n^{-1}(s) \cong \frac{J(\lambda)}{J_n} \qquad \text{..............................(4)}$$

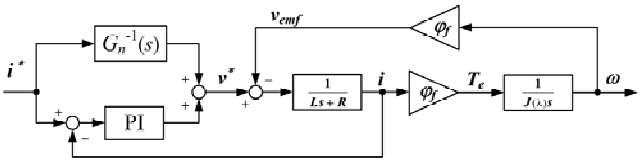
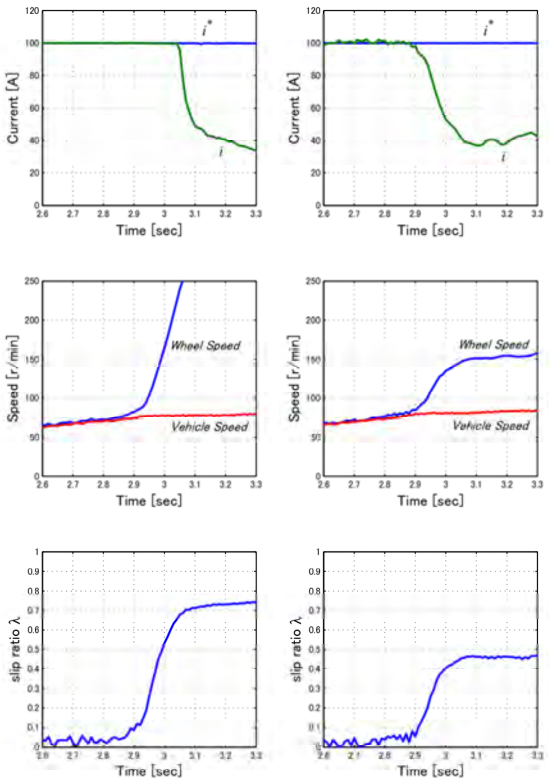


Fig. 1. Block diagram of FF + FB current control system.



(a) FB current control (b) FB + FF current control

Fig. 2. Experimental results of skid prevention.

When there is no tire slip (λ = 0), the actual motor current becomes equal to the reference value because $J(\lambda)/J_n$ is almost equal to 1. When tire slip occurs (λ > 0), $J(\lambda)$ becomes considerably smaller than J_n. The motor current required for the tires to prevent tire slip is only $J(\lambda)/J_n$ times that of the reference value. The P&I controller's gain should be decreased in order to reduce the effect of FB current control and to suppress tire slip in a short time interval. In a long time interval, the FB controller is activated again to realize the reference value of acceleration torque.

Fig. 2 shows the experimental results of skid prevention. The EV used in this study starts with a constant current of 100 A on a dry asphalt road and enters a wet road at around t = 2.9. A conventional FB current control system and the proposed FF + FB current control system are compared. Obviously, in the FB current control system, the rotational speed of the motor rapidly increases when tire slip occurs. In contrast to this, in the proposed FF + FB current controller, the motor speed decreases when tire slip occurs.

The torque reduction characteristics of EVs can be modified by estimating the back EMF [9][10], but the details this method are not presented herein.

3. Smooth Torque Control Assisting Gearshift Operations in Motor-assisted Automated Manual Transmission (AMT) Control Systems

Motor-assisted AMT control systems are highly efficient transmission systems. The concept of these systems is shown in Fig. 3. In these systems, a motor generates driving torque only when the neutral gear or clutch is pressed. In these systems, the required torque should be very large and generated quickly, but it need not be applied for a long time. Therefore, EDLCs are suitable energy storage devices for producing large power instantly in these systems.

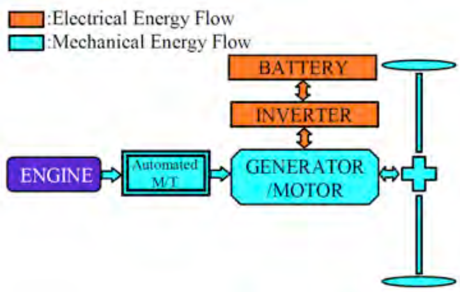


Fig. 3. Concept of motor-assisted AMT system

To operate these systems smoothly, we propose a disturbance observer-based controller. The configuration of the controller is shown in Fig. 4.

First, the controller produces the target driving torque T_{trg} according to the vehicle status, e.g., the acceleration pedal angle, brake pedal position, etc. Next, the shift, throttle, and brake controls are activated independent of the motor control. Because the motor torque can be measured easily, the disturbance torque in the motor, T_{obs}, can be calculated from the torque current component i_q and the wheel speed ω_{out} as

$$T_{obs} = \Phi_0 i_q - Is\omega_{out} \qquad \text{..............................(5).}$$

where I and Φ_0 are the nominal inertia of the vehicle and the torque coefficient, respectively.

The principle of motor-assisted AMT control systems is exactly similar to that of the disturbance observer-based controller. As T_{obs} also includes the engine torque, the brake torque, etc., the motor torque T_{trg_m} required to realize smooth gearshift operations can be easily obtained from (6) and does not require any information on the status of the clutch. In other words, we can easily estimate the status of the gears and the clutch without using any additional sensors.

$$T_{trg\_m} = T_{trg} + T_{obs} \qquad \cdots\cdots(6)$$

Fig. 5 shows the simulation result of motor-assisted AMT control. From Fig. 5(b), it is observed that by motor-assisted AMT control, the vehicle acceleration does not decrease with decreasing engine velocity. This result shows that smooth gearshift operations can be realized.

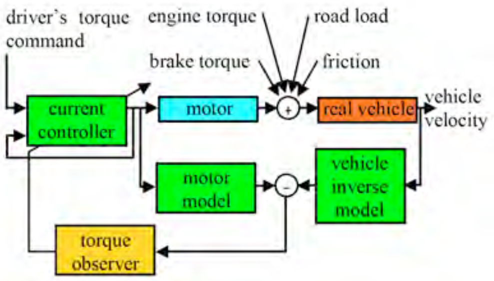
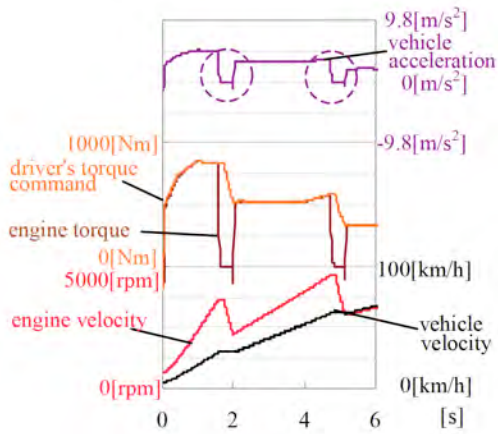
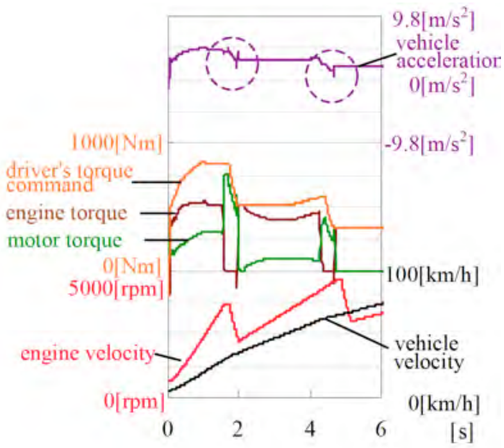


Fig. 4. Configuration of motor-assisted AMT control system.



(a) without motor assistance



(b) with motor assistance

Fig. 5. Simulation results of motor-assisted AMT control.

4. Design of Hybrid Observer of Sideslip Angle β

A novel design for the hybrid observer of β is proposed; in this design the local approximation of the nonlinear tire model is used.[15] Further, the fuzzy logic approach is also used to combine the local observer models so as to deal with the nonlinear properties of vehicle dynamics.

By choosing the membership functions along with weighting factors according to the tire slip angle α, the vertical load F_z, and the road friction coefficient μ, the proposed observer adapts to different running conditions including the changes in μ.

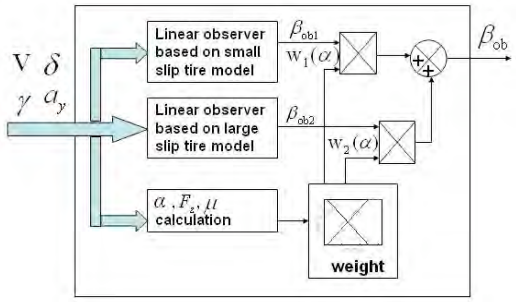


Fig. 6. Structure of hybrid linear observer.

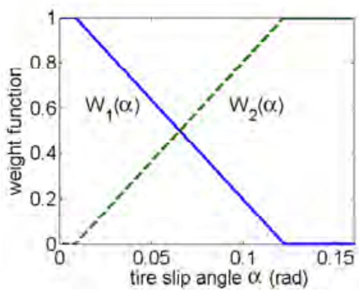
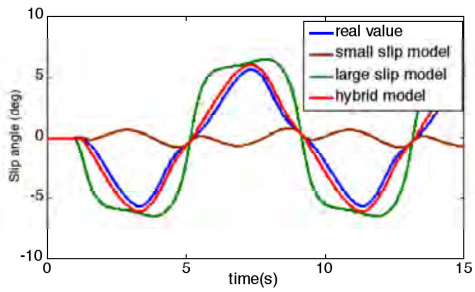
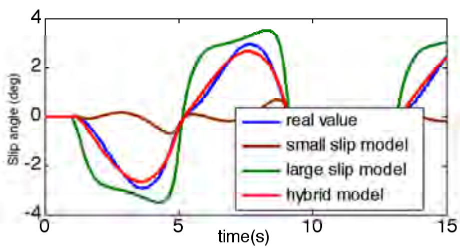


Fig. 7. Membership functions based on tire slip angle.



(a) large road friction coefficient ($\alpha = 0.85$)



(b) small road friction coefficient ($\alpha = 0.4$)

Fig. 8. Simulation results of slip angle estimation.

The hybrid observer is a combination of linear observers, as shown in Fig. 6. Each observer is designed by using the Luenberger observer, (11)(12)(26) and α is estimated for two different μ values from (7).

$$\beta_{ob}=\beta_{ob1}\cdot w_1(\alpha)+\beta_{ob2}\cdot w_2(\alpha) \qquad (7)$$

where $w_1(\alpha)$ and $w_2(\alpha)$ are the membership functions for the small and large slip models, shown in Fig. 7.

Simulation results obtained under different road conditions are shown in Fig. 8. The hybrid observer always follows the real values effectively. A practical application of this technology is shown in the reference (15).

5. Motion Control of EV C-COMS powered by EDLCs

We have been conducting experiments using relatively large vehicles such as University of Tokyo (UOT) Electric March II shown in Fig. 9. (4)~(8)

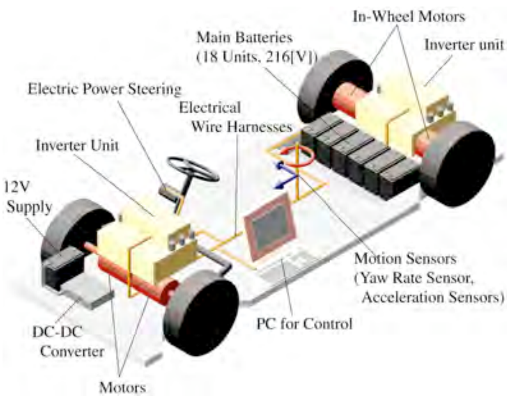
Because large vehicles are powered by conventional batteries, it takes a long time to charge them, and the batteries have to be frequently changed because the battery life is less than 500 cycles.

The new vehicles shown in Fig. 10 (12) are powered only by EDLCs. EDLSCs have several advantages overconventional batteries, as follow: (25)

(1) Capacitors can be charged and discharged very quickly without heat generation because there are no chemical reactions taking place inside them.

(2) Their energy level can be estimated very precisely from their terminal voltage.

(a) photograph UOT March II



(b) configuration of control system

Fig. 9. UOT March II.

(3) They are highly robust and can endure repeated charging and discharging.

(4) They are environmental friendly because they do not contain heavy metals.

Since EVs are powered by EDLCs, EVs are suitable for motion control experiments, in which various tests have to be performed under the same conditions in a short period.

The vehicle control system of C-COMS 1 is shown in Fig. 11. A Linux PC is used to calculate the reference torque in the inverter on the basis of the velocity of each tire, the steering wheel angle, the acceleration of the vehicle, and the yaw rate. The sampling time is 1 ms.

Fig. 10. C-COMS 1 and C-COMS 2.

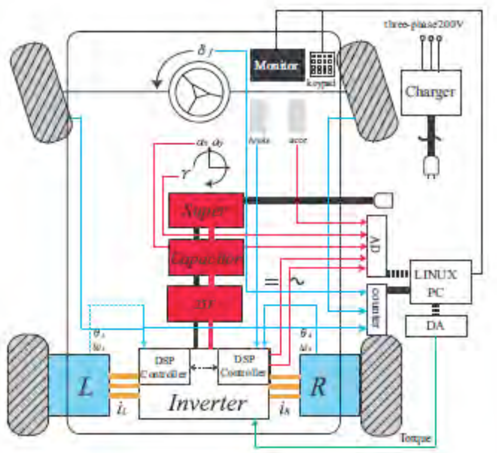


Fig. 11. Configuration of vehicle control system of C-COMS 1.

Three EDLC modules (approximately 100 V, 85 F) are installed under the driving seat, and a driving test is performed. Fig. 12 shows the total voltage and current of the capacitors.

These results explain some notable characteristics of EDLCs. Initially, the voltage of the capacitors decreases with increasing driving time, and the energy level of the capacitors can be estimated easily. Then, the voltage suddenly increases to approximately 3–4 V when the current direction changes due to the internal resistance of the EDLCs. Generally, since the resistance of EDLCs is small (80 mΩ), the fluctuation in voltage does not effect the system significantly.

Finally, the regeneration current is low when the capacitor voltage is relatively high and vice versa. This behavior indicates that the power regeneration in the inverter is regulated efficiently.

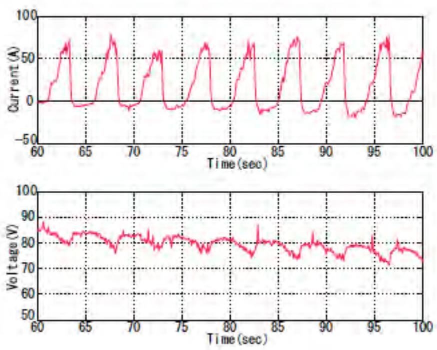
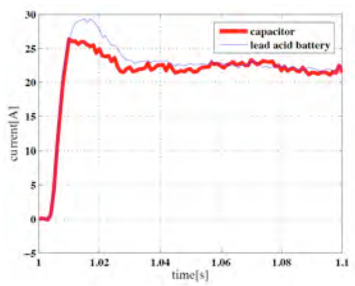


Fig. 12. Capacitor voltage and current during test.

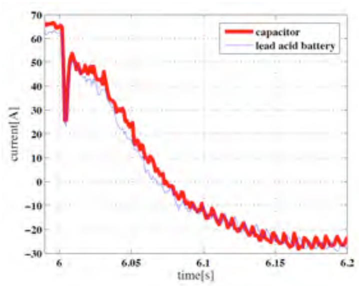
Recently, we have developed a new experimental vehicle C-COMS 2 that is also powered only by EDLCs and has two direct-drive in-wheel motors attached to the rear tires. [3] The EDLCs of C-COMS 2 are directly connected to inverters, and its ECU can change the torque inputs within 1 ms. Table 1 lists the various parameters of lead-acid batteries and the EDLCs installed in C-COMS 2.

Table 1 Comparison between lead-acid batteries and EDLCs.

	Lead-acid batteries (6 series)	EDLCs (3 series, 3 parallel)	Ratio
voltage	72 V	97.2 V	0.74
energy stored	3744 Wh	144 Wh	26
weight	130 kg	40 kg	3.25
vehicle weight	350 kg	260 kg	1.35
vehicle volume	47.3 L	44.21 L	1.07
internal resistance	21 mΩ	22 mΩ	0.96
range	45 km	2.5 km	18
time of charging	13 h	60 s	780



(a) start of driving



(b) during braking

Fig. 13. Comparison of inverter input currents.

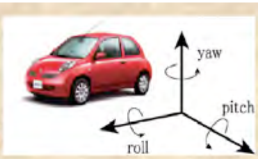
The energy stored in lead-acid batteries is 26 times larger than that of EDLCs. On the other hand, the charging of EDLCs is 780 times faster than that of lead-acid batteries, indicating that EDLCs can be charged in various ways, as required.

Table 1 also indicates that, when EDLCs and lead-acid batteries could have stored the same amount of energy, the range of EDLCs is longer than that of lead-acid batteries. This difference in range is attributed to the longer discharge time of EDLCs as compared to other energy storage devices, because EDLCs are physical batteries, and not chemical batteries. An important advantage of EDLCs over lead-acid batteries is their extremely higher power density, especially when they are charged.

In the experiment, we have suddenly accelerated and applied brakes in C-COMS 2 in order to verify the difference between EDLCs and lead-acid batteries. Fig. 13 shows the comparison of the inverter input currents at the start of driving and at braking. These figures show that the response of current is almost the same, and no distinct differences are observed between EDLCs and lead-acid batteries. In the future, we have to carry out more experiments on vehicle motion control and realize the goals listed in Table 2 [13][14] by utilizing the various advantages of EDLCs.

Table 2 Possible motion controls to be realized in EVs.

(1) TCS (traction control) based on MFC
(2) Slip prevention using Back-EMF Observer
(3) Hybrid ABS and TCS
(4) Adhesion Control emulating Separately Excited DC Motor's Property



(5) Estimation and Control of Body Slip Angle β
(6) DYC based on Yaw Moment Observer
(7) Estimation of μ Gradient and Peak μ Estimation using Brush Model and Driving Force Observer"
(8) Realtime Speed Pattern Generator to Improve Ride-comfort using Driver's Will Estimation
(9) Driving Force Distribution Control based on Estimation of Side Force

6. Contactless Power Transfer for EVs

EVs cannot cover a long distance like gasoline or diesel vehicles. Therefore, we have to develop new techniques to charge EVs quickly, several times a day, e.g., while parking or waiting at traffic signals. We expect that, in the future, EVs will be charged while running on the roads. To charge EVs or PHEVs, the vehicles have to be connected to a power source, which is not safe when there are occupants inside the vehicles. Contactless power transfer is the solution to this problem.

The concept of contactless power transfer, shown in Fig. 14, is quite old, and Nikola Tesla has already carried out experiments based on this concept. There is almost no air gap in typical electrical transformers, and the leakage flux in them is not a major problem. However, in practical applications, considerable attention has to be paid to leakage fields, which can be simulated easily. The electromagnetic field in electrical transformers changes dynamically due to small changes in their parameters. An analysis has revealed that contactless power transfer systems are highly efficient.

Our aim is to study higher frequency application using near field theory of electromagnetic wave resonance, [3] which should be the most robust to air gap and position variations.

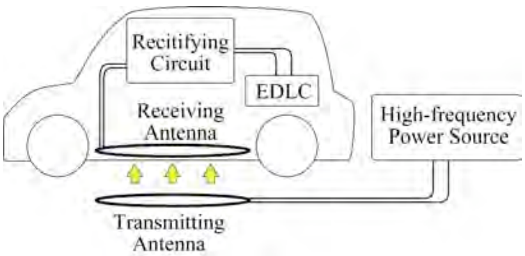


Fig. 14. Configuration of contactless power transfer system.

We plan to carry out research mainly on the following topics:

(1) Theory of contactless power transfer systems using near field theory of electromagnetic wave resonance
(2) Improvement of power transfer efficiency
(3) Robustness of contactless power transfer systems to position and air gap variations

7. Future Cars will Function like Trains

---- An excerpt from the interview with a key person at the Automotive Technology International 2008 Forum held at Makuhari in July 2008.

With the recent rapid developments in automotive electronics, how will cars change in the next 10 to 20 years?

The biggest change is that cars will be electrically powered, exceeding the meaning of the word "automotive electronics." It is not electricity or software that will run these cars; these cars themselves will be electricity. In other words, cars will be linked to electric power systems in the future. It is becoming more and more evident that gasoline vehicles will be replaced with hybrid and plug-in hybrid vehicles and then with pure EVs.

Of course, there are other possibilities also, such as clean diesel vehicles and biofuel vehicles, although our final target may be to develop efficient fuel cell vehicles. Trains, that were introduced one hundred years ago, have proved that electric motors are the best for actuators for conveyances if there is sufficiently good enough infrastructure developed to supply electricity to EVs.

In this context, the shift from hybrid cars to plug-in hybrid cars and to pure electric cars is becoming more and more prominent. This trend will become even more marked in the future due to the soaring oil price. When cars are connected to electric power systems, their characteristics will change. I mean, they will require only a small current for charging and will be charged quickly. In other words, they will function like electric trains.

What is the difference between trains and cars? Energy is supplied to trains from external sources when they are in motion, while cars carry energy storage devices to supply energy they require. Currently, cars run 400–500 km on single fueling at a maximum speed of 160 km/h, because automakers have made efforts to develop cars that can be used "anytime, anywhere and by anyone."

However, do all cars really have to possess these capabilities? Considering the conditions under which cars are used practically, I think many people would be satisfied with cars that can run 20 km a day at a maximum speed of 100 km/h. The distance of 400–500 km is sufficiently long to drive up to the middle of the Sahara Desert. It does not make sense to use such types of cars in urban areas. When I talk about a car that can store a small amount of energy, people often ask me, "What will you do if it runs out of energy?" But my question is, "How many people drive to areas where they cannot recharge their cars until their cars run out of energy?" We just need cars that meet our requirements.

(a) photograph

(b) quick recharging at bus stop in 30 s

Fig. 15. Capacitor bus operated in Shanghai.

My next question is, "What types of electronic technologies are the keys to realize these types of cars?" If cars are connected to electric power systems and can be frequently recharged, capacitors can be easily used to power these cars. Unlike trains, overhead wires cannot be stretched along roads to recharge electric cars. Further, they cannot carry sufficient energy sources to run 400–500 km, like gasoline vehicles.

Hence, we have to develop an infrastructure for frequently recharging electric cars. These cars should be fitted with devices that enable quick recharging and discharging.

Then, which is the best energy source for plug-in hybrid vehicles—secondary batteries and capacitors? I would prefer the latter because they have high current capability and can be charged quickly. The discharging rate of secondary batteries is high, but it takes time a longtime to charge them.

For example, plug-in hybrid vehicles with secondary batteries have to be charged for 1–2 h. Though some people predict that the charging time will be reduced to approximately 15–20 min in the near future, it is yet to be achieved. In this respect, vehicles powered by capacitors can be charged in approximately 30 s, e.g., the capacitor busses operated in Shanghai, shown in Fig. 15. Quick charging is the main advantage of capacitors.

Capacitors have several useful characteristics. (1) They have long operating life because no chemical reaction occurs in them during charging or discharging. (2) Their energy level can be accurately determined by checking their terminal voltage. (3) They are environmental friendly since they do not contain heavy metals. However, the energy density of capacitors is still lower than that of secondary batteries such as Li-ion batteries. Nevertheless, the energy density of capacitors will increase in the future due to technological advances. However, I think that their advantages are sufficient for their use in EVs.

8. Conclusion

The aim of our study is to develop advanced motion control techniques for EVs. We have proposed some research projects at the Hori Laboratory, The University of Tokyo, related to the motion control of EVs. New technologies and energy storage and supply devices such as capacitors are used in these projects.

We have shown that EVs are not only environmental friendly cars but also have advanced controls. In the future, we will study the critical problems of energy storage and supply in EVs and solve those problems using advanced devices and techniques.

Future EVs will be more environmental friendly and safe to drive. Undoubtedly, future vehicles will be driven by electric motors. Automobile engineers know this fact most well, because they gave their biggest events the name like “Tokyo Motor Show.”

The recent studies on EVs have mainly focused on their energy efficiency and environmental friendliness. In the future, we plan to develop high-performance EVs with advanced motion control systems.

Finally, we would like to express our thanks to past students of Hori Laboratory who have made contributions to our research on EVs and to many people from industries who have supported our projects.

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