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Driving Performance Improvement of Independently Operated Electric Vehicle

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Abstract

Recently, due to improvement of vehicle driving performance improvement by independent operation per vehicle wheel and fuel efficiency improvement by simplification of driving system, the study on independently operable in-wheel motor is actively in progress. The commercialization, however, is delayed due to security of durable performance and credibility of actuator, security of vehicle safety in case of drive motor malfunction, and reduced ride & handling performance due to weight increase of wheels. In this study, in order to resolve the ride & handling issue and fuel efficiency among such, electric vehicle applied with independent operation was modelled using MATLAB/Simulink, and CarSim was utilized to perform dynamic analysis of vehicle. The simulation environment thus constructed was used to execute development and verification of driving power distribution algorithm for driving efficiency improvement and control algorithm for vehicle steering performance improvement in order to secure base technology for driving performance improvement of independently operated vehicle.

Keywords: In-wheel Motor, Electric Corner Module, Yaw Moment Control, Power Distribution

1 Introduction

Independently-operated electric chassis system has the advantage such as fuel efficiency improvement by driving system simplification, vehicle driving performance improvement by independent operation per wheel, and increased space efficiency due to removal of coaxial motor, decelerator, differential gear and such to secure vehicle design freedom and to enable passenger space security. Also, the motor with faster response characteristics than the engine is used as the independent driving source so that it has the advantage that ABS, TCS, VDC and such technology can be implemented without additional devices. Due to such reasons, various automobile and component companies around the world are conducting various researches to secure source technology of independently-operated electric chassis system, but the application is being delayed due to issues such as security of credibility related to system durable performance, vehicle safety security during driving motor fail, ride & handling performance reduction according to increased wheel weight and such. This study intends to secure base technology to resolve the issue from the perspective of ride & handling and fuel efficiency among various issues of such electric chassis system. To resolve the issue, first the simulator that can evaluate the driving performance of the vehicle was developed. Using MATLAB/Simulink, the small-sized electrical vehicle applied with independently-operated electric chassis system was modelled, and vehicle dynamics was modelled using CarSim which can conduct vehicle dynamic analysis of 27 degrees of freedom. The developed simulator helps to find the dynamic characteristics of straight driving/turning/acceleration/braking of the vehicle under various conditions, and thus secure the base technology for improvement of ride & handling performance and driving fuel efficiency of independently-operated electric chassis system.

2 Development of Independently Operated Electric Vehicle Simulator

The vehicle intended in this study is a small-sized electrical vehicle applied with independently-operated system. The vehicle applied with such independently-operated system can independently operate left and right wheel, so the technology to secure vehicle stability following such is a priority issue. To resolve this, the control logic of driving safety of independently-operated system must be first developed, and it is very difficult to develop and verify driving control algorithm while the system of target vehicle is not yet completed. Thus, this project intends to resolve such issue by developing an environment that simulates the target vehicle in S/W environment and is able to analyse vehicle dynamic characteristics.

2.1 Battery Modeling

Figure 1: Battery I/O signal

Input and output signals of the battery model are shown in Figure 1. Since charging and discharging of the battery is continuously carried out according to operating state of the motor, SoC (State of Charge) and charging property of the battery must be taken into consideration. In this paper, I/O power and SoC of the battery were calculated using an internal resistance model that reflects such battery characteristics. Battery voltage upon discharge and charge according to Kirchhoff's law is as follows.[10]

$$U_a = E - i_a R_i \qquad \text{discharge} \qquad (1)$$
$$U_a = E + i_a R_i \qquad \text{charge} \qquad (2)$$

Current characteristic during charge and discharge was induced as in Eq. (3) and (4) using battery voltage, battery power and relation function with current. Battery voltage and internal resistance values according to SoC used for calculation of current characteristic were found as shown in Figure 2 through OCV (Open Circuit Voltage) experiment.

$$i_a = \frac{E - \sqrt{E^2 - 4R_i P_{battery}}}{2R_i} \qquad \text{discharge} \qquad (3)$$

$$i_a = \frac{-E + \sqrt{E^2 - 4R_i P_{battery}}}{2R_i} \qquad \text{charge} \qquad (4)$$

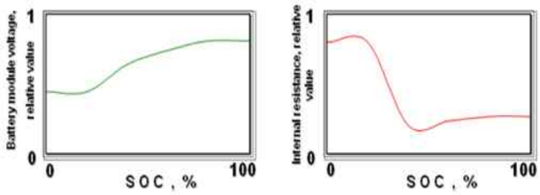

Figure 2: Battery module voltage and internal resistance following SOC

2.2 Motor Modeling

The motor model, as shown in Figure 3, was composed to output angular velocity and torque of the motor through velocity, battery output, demanded operating power, and demanded regenerative braking torque. Here, maximum output torque of the motor is determined by angular velocity of the motor.

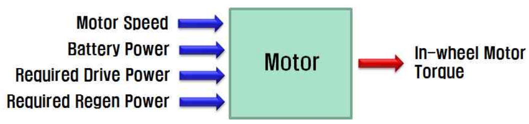

Figure 3: Motor I/O signal

In this paper, simple modeling was done using output torque according to angular velocity of the motor and motor efficiency characteristics according to torque. Data used for modeling are the results of dynamo experiment on the motor. Lastly, the motor model was composed as shown in Figure 4 using MATLAB/Simulink.

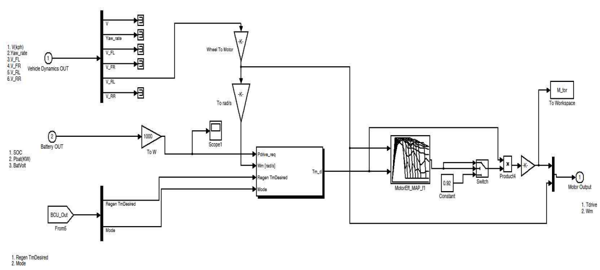

Figure 4: Motor modeling using MATLAB/Simulink

2.3 Vehicle Modeling

For driving safety evaluation on vehicle, a vehicle dynamic analysis simulator with multiple degrees of freedom is required. In this study, an attempt was made to resolve such problem by constructing a co-simulation environment between the above simulator based on MATLAB/Simulink and CarSim, a commercial vehicle dynamic analysis program, for vehicle dynamic analysis with multiple degrees of freedom. Figure 5 shows the co-simulation environment between MATLAB/ Simulink and CarSim. Torque of the motor calculated from MATLAB/Simulink is entered into left / right rear wheels of the vehicle. Also, EMB braking force of 4 wheels is entered into CarSim. CarSim uses the received signal to calculate velocity of the vehicle, velocity of each wheel, and behavioral characteristics of the vehicle. It enters velocity of the vehicle and yaw rate velocity of left / right rear wheels of the vehicle into MATLAB/Simulink. As such, an environment for evaluation of driving safety control logic for the electric chassis system to be developed in the future was constructed based on closed-loop simulation environment. Table 1 shows detailed specification of the developed vehicle model.

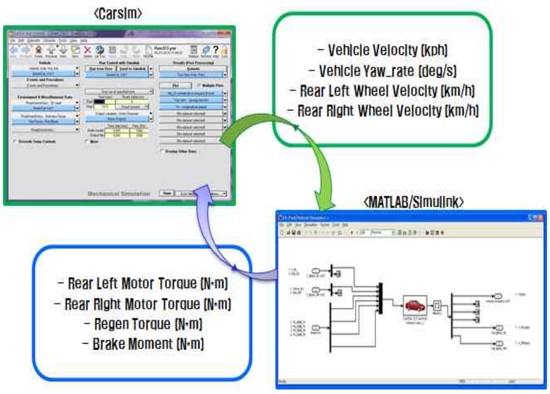

Figure 5: CarSim-Simulink co-sim environment

Table 1 Specifications of in-wheel electric vehicle

Component	Specification
Sprung Mass	1231.1 kg
Unsprung Mass	132.5
Vehicle height	1160 mm
Vehicle width	1780 mm
Wheel base	2347 mm
Tire radius	292 mm
Distance of C.G to front wheel centerline	1311 mm
Roll inertia	505.9 kg·m^2
Pitch inertia	2011.8 kg·m^2
Yaw inertia	2064.5 kg·m^2
In-wheel motor	15 kW
Battery	65 kW/ 60 Ah

3 Yaw Moment Control Algorithm of Independently Operated Electric Vehicle

As independently-operated electric chassis system can independently operate/brake each wheel, it has the advantage of stably controlling the vehicle under various circumstances. Under circumstances such as vehicle rotation or asymmetrical road driving, however, there is the issue that torque control of braking wheel must be efficiently achieved. To resolve such issue, torque vectoring technique was utilized. Torque vectoring technique creates the driving torque difference of left and right wheel to create yaw moment and thus improving the rotating force of the vehicle. Fig 6 shows the flowchart of the developed rotation control algorithm.

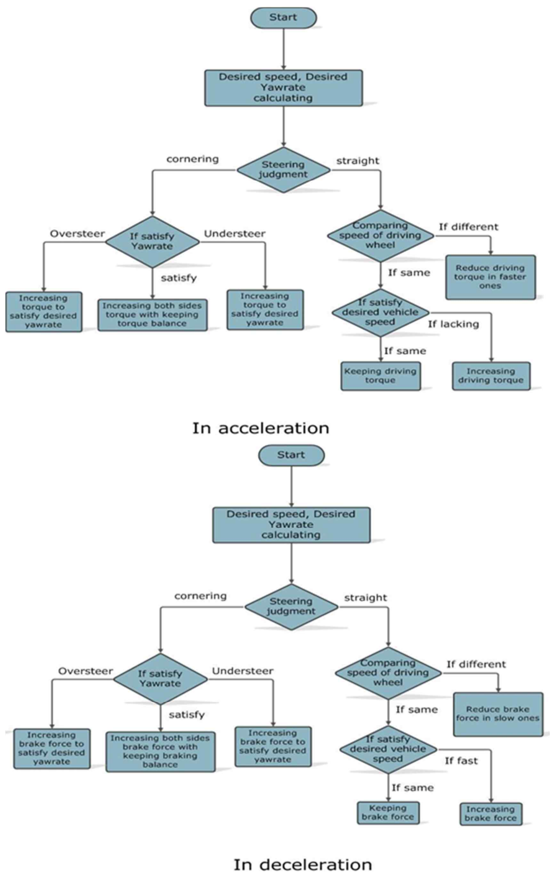

Figure 6: Direct yaw moment control algorithm flowchart

For performance evaluation of the developed algorithm the simulation of the vehicle with the control algorithm and the vehicle without the control algorithm was conducted. The test condition was road friction coefficient 0.85, initial speed 120km/h for execution of double lane change. Fig 7 shows the driving path of the vehicle applied with the control algorithm and the vehicle not applied with the control algorithm. The graph confirms that the vehicle applied with the control algorithm has less breakaway from the path than the vehicle not applied with the control algorithm.

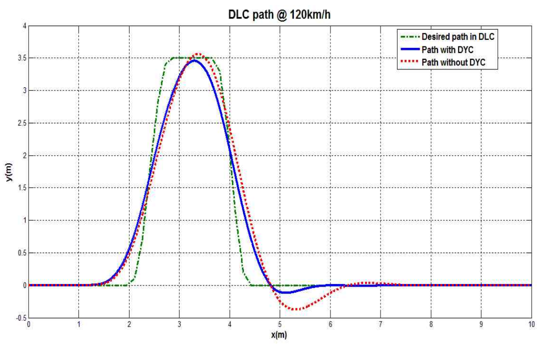

Figure 7: Result of target path tracing of double lane change simulation

4 Front/Rear Wheel Driving Power Distribution Algorithm for Improvement of Driving Efficiency

In the 4-wheel in-wheel electric vehicle as the subject of this paper, in-wheel motor is attached to each wheel. However, while there are cases in which large torque is necessary, there also are situations in which large torque is unnecessary depending on the conditions such as cruise control, elastic drive and downhill drive. Since operation of all wheels under such situation is inefficiency in terms of energy, this study attempted to improve driving efficiency using a control algorithm that switches between 2-wheel drive and 4-wheel drive.

4.1 Driving Mode Judgment Algorithm

For development of 2-wheel / 4-wheel drive switch algorithm, an algorithm determining driver's intent to accelerate or drive in cruise mode must be developed first.

In this paper, α using acceleration pedal value of driver was defined as Eq. (5) to determine driver's intent.

$$\alpha = \frac{vehicle\ \ velocity}{throttle\ \ open\ \ ratio} \tag{5}$$

The value of α becomes relatively small during acceleration because throttle open ratio is increased compared to velocity, and it becomes relatively large during cruise control because throttle open ratio is decreased compared to velocity. Table 3 shows the value of α considered as cruise control for different velocities.

Table 2 α according to vehicle velocity

Velocity	α
30km/h	21
60km/h	13
80km/h	10
100km/h	8

4.2 Driving Torque Distribution Algorithm

By comparing the reference value of α found in the previous section and α calculated during actual drive of vehicle, driver's intent to accelerate is examined to choose between 4-wheel drive and 2-wheel drive according to driver's intent and vehicle status. Table 3 shows the vehicle status used as criteria for judgment, and Figure 8 shows the flow chart of the control algorithm.

Table 3 Vehicle status according to A_p , B_p , V

A_p	B_p	V	Mode
0	0	0	Stop
0	0	1	Cruise
0	1	0	Stop
0	1	1	Deceleration
1	0	0	Stop
1	*0*	*1*	*Acceleration or cruise*
1	1	0	X (Stop)
1	1	1	X (Deceleration)

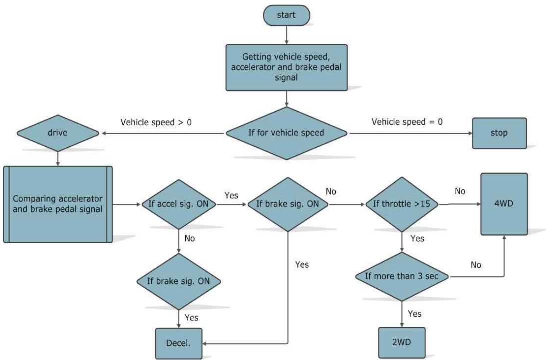

Figure 8: Vehicle driving state judgment algorithm flowchart

The developed control logic was applied and simulation was conducted by accelerating to 80km/h and 100km/h respectively with maximum acceleration and constant-speed driving for 2,000 seconds. Fig 9 shows the SOC comparison result graph according to the existence of torque distribution algorithm control logic obtained through the simulation.

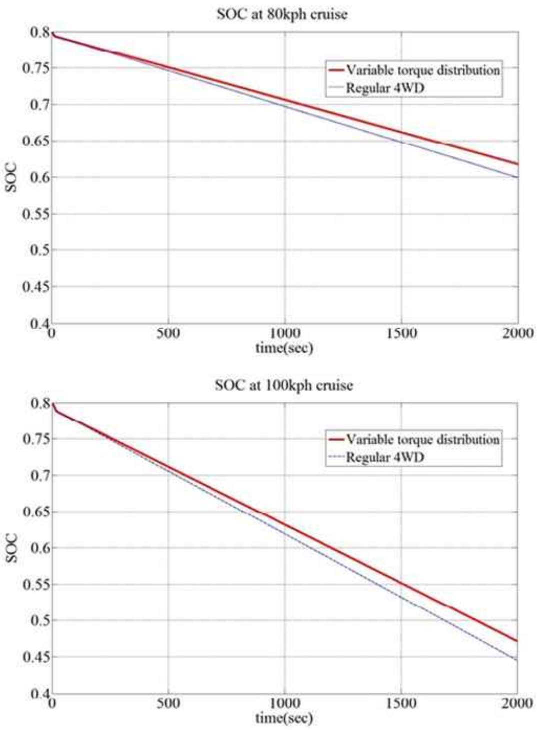

Figure 9: SOC comparison according to existence of torque distribution algorithm at constant-speed driving

Second condition was set to FTP-75 mode for SOC comparison. The experimental results are shown respectively in Fig 10. SOC was changed much while cruising and slightly during city drive. Front and rear wheels torque distribution algorithm was verified to show better driving efficiency.

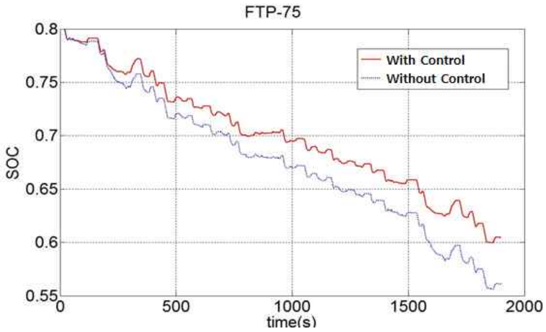

Figure 1 SOC comparison according to existence of torque distribution algorithm at FTP-75

5 Conclusion

To construct the environment for driving safety performance evaluation of small-sized electrical vehicle applied with independently-operated electric chassis system, a simulator was developed. For vehicle driving performance evaluation, MATLAB/Simulink and CarSim was used to model the target vehicle. The performance evaluation environment constructed as such was used to secure vehicle driving stability performance evaluation-based technology. Also, to improve the driving stability of vehicle applied with independently-operated electric chassis system, torque vectoring technique was introduced. For this, the algorithm to compute demanded rotation amount was proposed, and the control algorithm was developed to follow the proposed rotation amount in demand. To verify the developed algorithm, simulation was conducted. As the result of simulation, the driving stability of the vehicle applied with torque vectoring was confirmed to be greatly enhanced. In future, the developed algorithm will be verified after constructing a vehicle applied with the independently-operated system.

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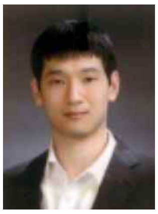

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