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Performance Evaluation of Electro-Hydraulic Brake for Fuel Cell Vehicles using Hardware-in-the-loop Simulation

Jeong Hun Choi [1], Jun-Sang Yun[1], Bin Wang[1], Jaihyun Shin[1], Hoon Yeo [2], Sung-Ho Hwang[1]
[1] School of Mechanical Engineering, Sungkyunkwan University, Suwon 440-746, Gyeonggi, Korea,hsh@me.skku.ac.kr
[2] Hyundai Mobis, Yongin 446-912, Gyeonggi, Korea

Abstract

Nowadays, various researches about eco-friendly vehicles such as hybrid electric vehicle, fuel cell vehicle and electric vehicle have been actively carried out. Since most of these green cars have electric motors, the regenerative energy technology can be used to improve the fuel economy and the energy efficiency of vehicles. In order to apply the regenerative braking, the research and development on electronic brake system such as EMB(Electro Mechanical Brake), EWB(Electro Wedge Brake), and EHB(Electro Hydraulic Brake) are necessary which can actively control the physical braking power according to the regenerative breaking power of the motor unlike the existing hydraulic brake system.

In this paper, EHB system for fuel cell vehicle was developed, and the hardware-in-the-loop simulation(HILS) is performed to analyze the characteristics of the EHB system and the regenerative braking system for fuel cell electric vehicle.

Keywords: Electro-Hydraulic Brake, Fuel Cell Vehicle, Regenerative Braking, Performance Simulator, HILS(Hardware-in-the-loop Simulation)

1 Introduction

Recently, various environmental / energy resource-wise issues are inducing active research and development in environment-friendly vehicles such as electric vehicle (EV), fuel cell electric vehicle (FCEV) and others, where regenerative braking is being researched as a core area for fuel efficiency improvements.

For application of such regenerative braking technology, the research and development on electric brake system such as EMB, EWB and EHB which can actively control physical braking power according to regenerative braking power of the motor should also be conducted at the same time. At the early stage of electronic brake system development, the performance characteristics according to the change in the cooperation control algorithm between regenerative braking and mechanical braking considering the driving stability and energy efficiency of the vehicle must be understood. Therefore, in order to save the initial cost and time for development under the circumstances of various system requirements, V-process must be achieved where design and performance test using simulator occur at the same time, and it is necessary to secure the reliability of simulator through HIL simulation result analysis. [1]

In this study, the performance of EHB was evaluated by executing HILS based on the fuel cell vehicle simulator. Also, the response characteristics analysis was executed on the brakes which were then applied to fuel cell vehicle simulators, and in order to reduce the deceleration change in the transient region during the regenerative braking, the cooperation control algorithm between the regenerative braking and EHB system was developed.

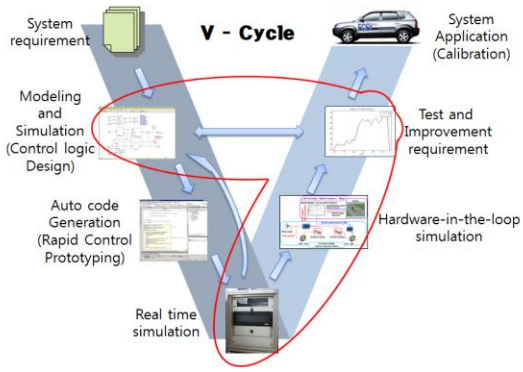

Figure1: V-process and HIL Simulation

2 The Performance Simulator of the Fuel Cell Vehicle

The Fuel Cell Vehicle Simulator set up for The target fuel cell vehicle by MATLAB/Simulink. The modeling of major components was respectively executed based on performance curve, characteristics map, transient state characteristics, and kinetics, and the battery employed the batter SoC (State of Charge) according to the characteristics of internal resistance. The traveling mode was divided into acceleration, constant speed, and stop, and each controller was modeled, and the driver modeling was executed for the driver reaction per each mode. The kinetic behavior analysis of the vehicles utilized CarSim set for specification of the target fuel cell vehicle Figure2 shows the structure of The Fuel Cell Vehicle Simulator. [2]

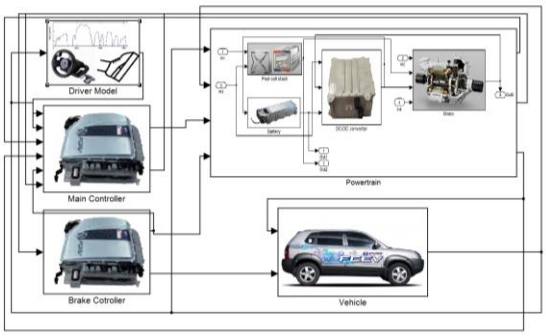

Figure2: Fuel Cell Vehicle Simulator

2.1 Fuel Cell Modeling

The fuel cell was modeled using the characteristics map. The required power for the vehicle according to the acceleration pedal is taken as the input and the appropriate voltage and current are outputted.

2.2 Battery Modeling

The battery is discharged in the motoring mode or when power is required externally, and is charged by the regenerative braking of the generating mode or by the fuel cell stack. The charge-discharge relation expression of the battery is as follows.

$$i_{\alpha} = \frac{-E + \sqrt{E^2 + 4R_i P_{battery}}}{2R_i} (charge) \qquad (1)$$

$$i_{\alpha} = \frac{E - \sqrt{E^2 - 4R_i P_{battery}}}{2R_i} (discharge) \qquad (2)$$

2.3 Motor Modeling

The motor was modeled using the performance curve. Speed, fuel cell output, required driving output, required regenerative braking torque are taken as the input, and the acceleration and torque of the motor are outputted, and the outputted torque and motor speed go through the efficiency map and then are outputted as actual motor torque.
The motor torque is divided into motoring and generating, and the charge/discharge of the battery is achieved by mode.

2.4 DC/DC Converter Modeling

In case of a vehicle that uses a motor, the voltage of fuel cell stack or battery and the operative voltage of the motor differ so that a converter which converts the voltage is necessary. DC/DC converter converts the inputted direct current to alternating current and adjusts the voltage, and then converts it into a direct current with a changed voltage and output it.
When discharging, the input value of the battery voltage determines the voltage of the fuel cell stack, and when charging, the input value of the fuel cell stack voltage determines the voltage, and the conversion efficiency varies depending on the voltage ratio, and is different for when charging and when discharging. The formula below shows the voltage ratio relation expression when charging and when discharging.[3]

$$Voltage\ ratio = \frac{V_{battery}}{V_{bus}} (charge) \qquad (3)$$

$$Voltage\ ratio = \frac{V_{bus}}{V_{battery}} (discharge) \qquad (4)$$

2.5 Controller

The controller largely consists of Main Controller and Brake Controller.

In the closed loop simulation, the computation of output values required by input of each variables is necessary, and for fuel cell vehicle simulator, the input values of current vehicle speed, required speed, acceleration and brake pedal location, battery SC, fuel cell stack voltage, motor angular velocity and such are received and the output values of fuel cell power, fuel cell required power, battery required power, regenerative braking required power, fuel cell operability, vehicle traveling mode, required braking power, batter voltage and such are required.

Therefore, for each of the 5 traveling modes of the vehicle – start, acceleration, general traveling, deceleration, and fuel cell stop, the internal algorithm of the controller determines the value for each variable. [4]

2.6 Linked Simulator

The kinetic behavior analysis of the vehicles utilized CarSim. The linked simulation of MATLAB/Simulink which modeled the major components and Carsim of the vehicle model is necessary. [5]

The acceleration, brake, and steering values outputted from the driver model of Simulink determine the output of fuel cell in the controller model, according to which the operative power is outputted from the motor, which is transferred to the vehicle model of the Carsim, and the simulation is executed, then the current vehicle speed and yaw rate according to the kinetic behavior characteristics of the vehicle are again transferred to the Simulink controller values and converted into appropriate output values, and this constitutes the cyclic simulation of vehicle control. The modeling for each component can be confirmed in Figure3.

3 Electro-Hydraulic Brake(EHB)

The electro-hydraulic brake(EHB) is developed in various forms, and is utilized most representatively in Toyota Prius. EHB used in this report has the existing manual brake applied to the rear wheels, and operates the master cylinder using the electric motor, which exerts the hydraulic pressure on the front wheels. From the front/rear required braking force calculated according to the braking force distribution algorithm at the braking of the vehicles, the front wheel required braking force excluding the regenerative braking force enables the physical braking force to variably take control. Figure4 shows the EHB schematic diagram.

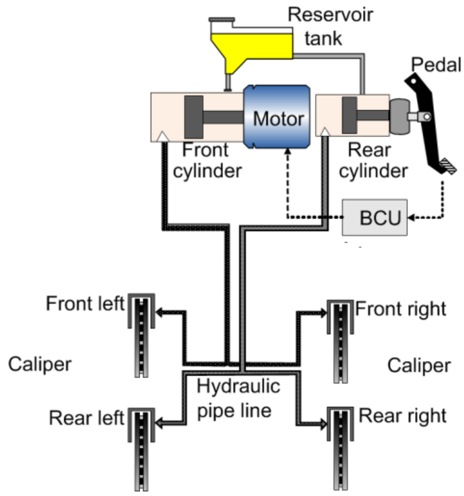

Figure4: Electro-Hydraulic Brake structure diagram

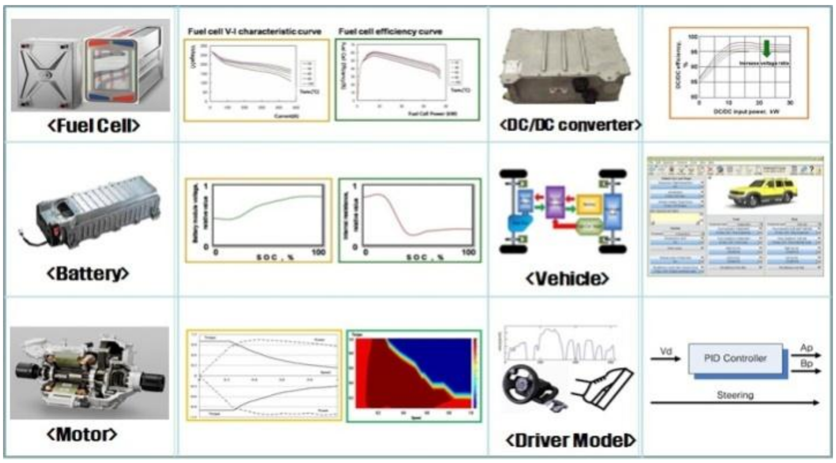

Figure3: Fuel-Cell Vehicle modeling

3.1 Brake Response Characteristics

In the performance simulator where the modeling for brakes are not separately applied, the front/rear braking power calculated in the brake controller is inputted directly into the Carsim and the simulation is executed. Because the response characteristics of the actual brake is not considered, the credibility of the simulation results values are inadequate, and in a system which occurs in a short period of time such as regenerative braking transient region characteristics, the influence of characteristics due to the transfer function of the model is more important.

The importance of the theoretical analysis model of the target system is also great, but an assumption which lacks practicality is included, and especially the systems that have complex theoretical models or are difficult to process their physical processes, and are sensitive to environmental changes such as the hydraulic system, the modeling using experimental data is effective. [6]

In this study, to figure out the transient response characteristics, the response experiment data of EHB system regarding the step signal among natural signals was used. In Fig. 5, it can be confirmed that the wheel cylinder pressure response for the 100 bar step input shows about 0.2 seconds of delay of transient characteristics.

The transfer function modeling using the experiment data of response characteristics is assumed to be the sum of exponential function and was estimated as an appropriately low value.

Expressing the target system $\mu(t)$ which changes according to time t as the sum of exponential functions is as follows in Equation.

$$\mathcal{Y}(t) = \mathcal{Y}(\infty) + Ae^{-\alpha t} + Be^{-\beta t} + \cdots \qquad (5)$$

For linear curve fitting for Equation (5), log is applied to both sides, and then the A, B, α, β values appropriate for the response characteristics experiment data can be found.

$$\mathcal{Y} - \mathcal{Y}(\infty) \cong Ae^{-\alpha t} \qquad (6)$$

$$\log_{10}[\mathcal{Y} - \mathcal{Y}(\infty)] \cong \log_{10} A - \alpha t \log_{10} e \qquad (7)$$

$$\mathcal{Y} - [\mathcal{Y}(\infty) + Ae^{-\alpha t}] \cong Be^{-\beta t} \qquad (8)$$

$$\log_{10}[\mathcal{Y} - \mathcal{Y}(\infty) + Ae^{-\alpha t}] \cong \log_{10} B - \beta t \log_{10} e \qquad (9)$$

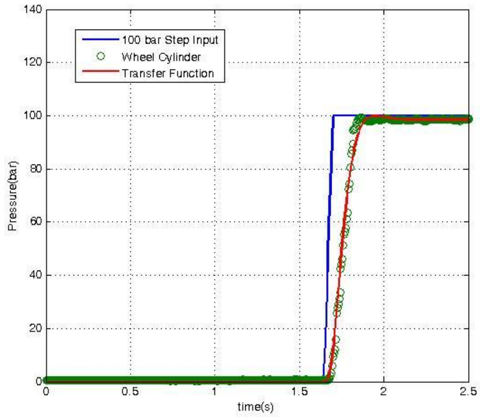

Figure5: Transfer function response

at 100 bar step input.

Figure5 shows the transient response characteristics graph which uses the experiment data to apply the modeled secondary transfer function, and has the same 100 bar step input. It can be seen that the response characteristics of the experiment data is appropriately reproduced.

3.2 Application of Brake Model

The previously analyzed characteristics model of EHB was applied to the performance simulator.

Before the front-wheel required braking power calculated in the brake controller was inputted to Carsim, the secondary transfer function which is the characteristic model of EHB was applied to acquire the same execution results as HILS.

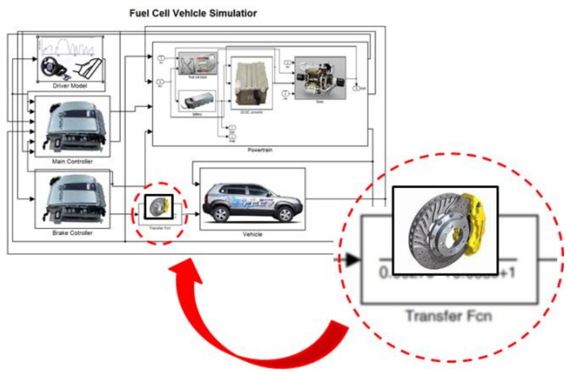

Figure6: Performance Simulator with Brake model

3.3 Simulation Result

Using the performance simulator with the brake model applied, the simulation to figure out the transient region characteristics was executed at 80km/h under 35% braking conditions.

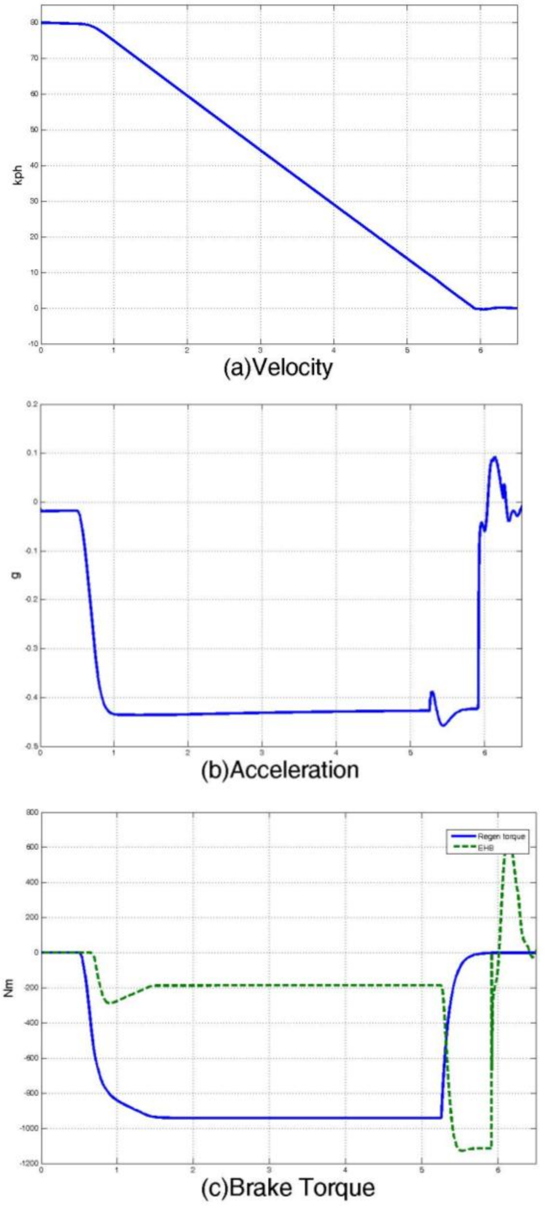

Figure7: Simulation Result

As it can be seen in Figure7, during early braking, the braking power occurs, and then the regenerative braking limit algorithm of brake controller limits the braking power, and the braking power of EHB to compensate this increases,[8] where a transient region occurs, and it can be confirmed that a change in acceleration occurs during the braking of the vehicle.

4 Analysis of Transient Region Characteristics

The change in braking power in the transient region is according to the different response characteristics respectively of regenerative braking power and physical braking power.[7] The quick control of physical braking power as in hydraulic brake is difficult to achieve, but the response control according to delay of regenerative braking power is relatively readily available. Also, the response of regenerative braking may differ depending on the motor types or the method of operative system used in the vehicle, so it is necessary to figure out such transient region characteristics according to response characteristics of regenerative braking.

Based on existing study results, two variables that influence transient region which were motor response characteristics and regenerative braking limit speed were varied to 3 levels and the change in transient region characteristics was observed.

Table1: Parameters of simulation

Control & Design variables	Control & Design variables		
	1	**2**	**3**
Motor Response Delay(sec)	0.00	0.02	0.04
Speed Limit(km/h)	10	15	20

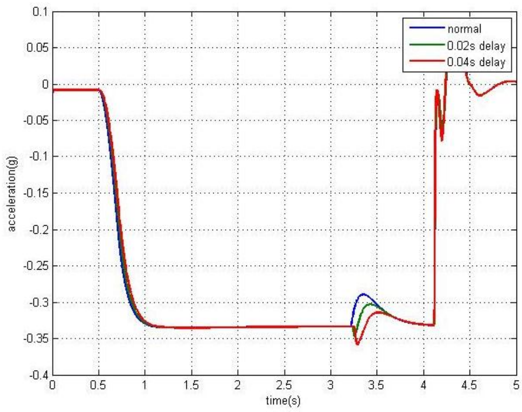

Figure8: Motor Response Delay

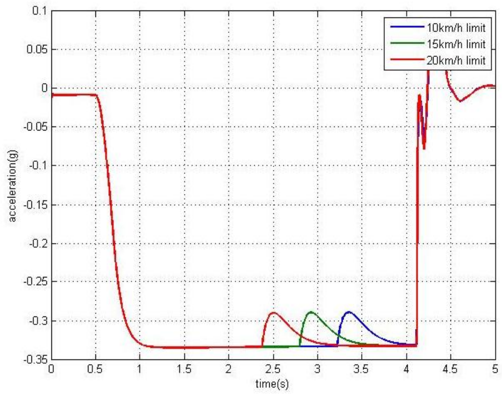

Figure9: Speed Limit

As in Fig. 11, the simulation results regarding the motor delay characteristics change shows that regenerative braking system has a faster response characteristic than the physical braking power so that longer response delay results in less deceleration change, but if this becomes too long, the entire braking power increases and the deceleration is shown to increase.
Examining the result of regenerative braking limit speed in Fig. 13, it can be confirmed that there is no change in the magnitude of deceleration, but only the occurrence time of transient region changes.

4.1 Cooperation Control Algorithm

To resolve change in deceleration which occurs in the transient region, cooperation control algorithm of EHB and regenerative braking was developed.
The cause of deceleration change in transient region is the lack or excess of the sum of regenerative braking power and physical braking power compare to the required braking power of the vehicle.
Figure10 shows block diagram of front EHB control system

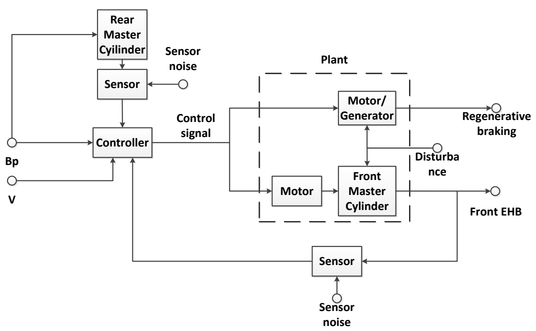

Figure10: Front EHB Control System Block Diagram

At braking, Brake controller calculates the required braking power according to the brake pedal amount, at the same time, the rear-wheel braking power which directly connected to brake pedal operates.
As The rear-wheel braking power excluded from the required braking power, the front-wheel braking power is decided. And then, available regenerative braking power is calculated according to the current vehicle speed.
Front EHB power is decided by comparing calculated front-wheel braking power with the available regenerative braking power.
Using control variables mentioned earlier, cooperation algorithm makes transient region longer to compare braking power and compensates lack of total braking power, As comparing actual hydraulic pressure measured from pressure sensor with required power of EHB.

5 Hardware-in-the-loop Simulation Environment

The environment to execute HILS with the electro-hydraulic brake and fuel cell vehicle simulator was implemented. For Real_Time, dSpace program and micro AUTOBOX were used to separately load the brake controller of the simulator and the rest power train, vehicle part and such, and the input/output was defined and CAN was used to input/output the signals. In the vehicle simulator, the required braking force calculated according to the brake pedal values was received at the brake controller as the input and converted into the required clamping force to operate the brake, and the actual pressure value measured by the pressure sensor is again received at the vehicle simulator as the input to change the kinetic behavior of the vehicle. Fig.4 shows the HIL Simulation environment.

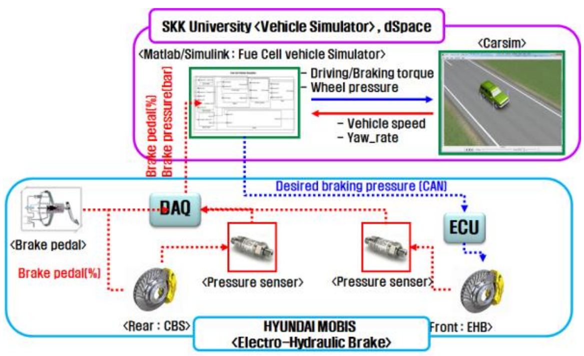

Figure11: HIL Simulation environment

5.1 HIL Simulation with Cooperation Control Algorithm

In the implemented HIL environment, the simulation to evaluate the performance of EHB and cooperation control algorithm.

The simulation was executed respectively with algorithm and without algorithm at 40km/h under 35% braking. The acceleration pedal implemented in HILS environment is used to reach the target speed and then brake pedal was applied.

Figure12 Figure13 show respectively HIL simulation result without/with cooperation control algorithm at 40kph, 35% Braking.

Figure (a) is vehicle velocity(kph), (b) is acceleration(g) and (c) is brake torque(Nm) of regenerative brake and EHB.

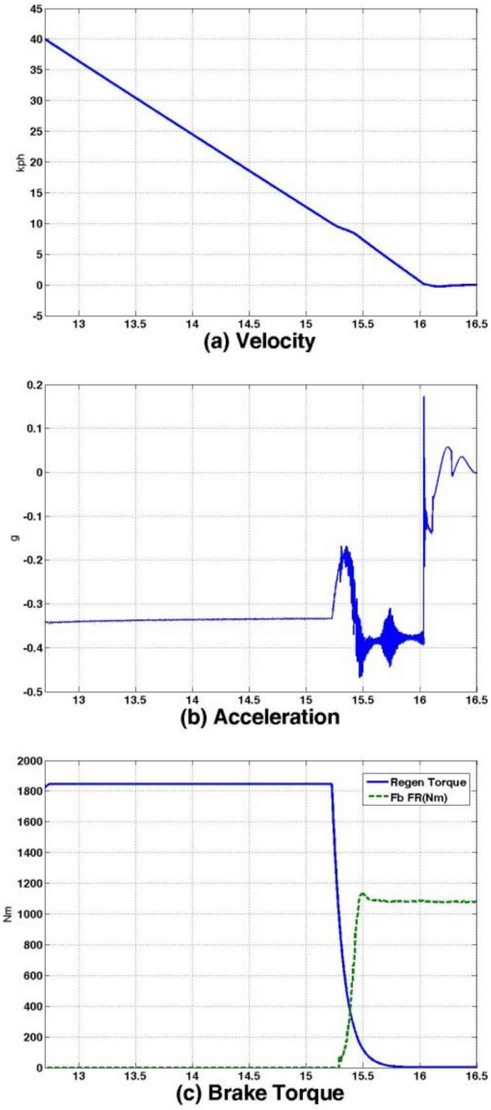

Figure12: HIL Simulation result without algorithm

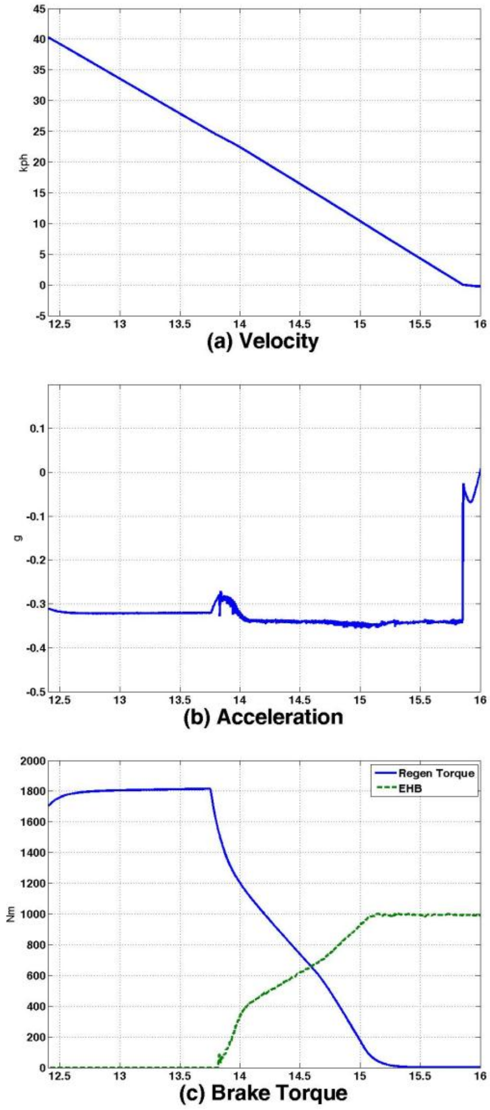

Figure13: HIL Simulation result with algorithm

As in Figure12 , without algorithm, when vehicle velocity reach 10kph, regenerative braking limit speed, brake controller limits the regenerative braking power. To compensate this, the braking power of EHB increases.

The range of this transient region is about 200~300msec, so the acceleration change occurs about 0.2~0.3g according to the different response characteristics of each brake system.

As in Figure13 , simulation result with algorithm, the regenerative braking power is limited at 25kph and decreases proportionally to vehicle speed.

Compared to without algorithm result, the range of transient region is longer, EHB and the regenerative brake can be controlled cooperatively.

As a result, it can be confirmed that the change in deceleration is reduced in the transient region and the deficient braking power due to initial motor characteristics is compensated by EHB power .

6 Conclusion

In this report, the performance evaluation of electro-hydraulic brake for fuel cell vehicle has been executed.

The environment to execute HILS with the electro- hydraulic brake and fuel cell vehicle simulator was implemented.

Using the experiment data regarding the step response of the electric hydraulic brake, the characteristics of transient state was modeled as the secondary delivery function, and was applied to the fuel cell vehicle simulator as the brake model to complement the credibility for the braking power response of the simulator.

In order to examine the characteristics regarding the deceleration change in the transient region of regenerative braking system, the delay response of the motor was varied to execute simulation and the basic data for establishing control strategy to stabilize the regenerative braking system was secured.

Cooperation control algorithm was developed to improve the change in deceleration in the transient region and evaluated to HIL simulation environment and the execution results confirmed that the change in deceleration was reduced.

Acknowledgments

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Authors

Jeong Hun Choi received the B.S. degrees in mechanical engineering from Sunkyunkwan University, Suwon, Korea, in 2011.
He is currently working toward the M.S. degree with the School of Mechanical Engineering, Sungkyunkwan University.
His research interests include the regenerative braking system and In-wheel motor vehicle control.

Bin Wang received the B.S. degree in computer science from Kunsan National University, Kunsan, Korea, in 2011.
He is currently working toward the M.S. degree with the School of Mechanical Engineering, Sungkyunkwan University, Suwon, Korea.
His research interests include the regenerative braking system.

Jun-Sang Yun received the B.S. degree in mechanical engineering from Hansei University, Gunpo, Korea, in 2009.
He is currently working toward the M.S. degree with the School of Mechanical Engineering, Sungkyunkwan University, Suwon, Korea.
His research interests include the regenerative braking system for electric vehicle.

Jaihyun Shin received the B.S. degree in mechanical design and the M.S. degrees in mechanical engineering from Sungkyunkwan University, Suwon, Korea, in 1989 and 1991 respectively.
He has worked in C&SPACE

Hoon Yeo received the B.S. degree in mechanical design and production engineering and the M.S. and Ph.D. degrees in mechanical engineering from Sungkyunkwan University, Suwon, Korea, in 2000, 2002, and 2006, respectively.

He has worked in Hyundai Mobis.

Sung-Ho Hwang received the B.S. degree in mechanical design and production engineering and the M.S. and Ph.D. degrees in mechanical engineering from Seoul National University, Seoul, Korea, in 1988, 1990, and 1997, respectively.
He is currently an Associate Professor with the School of Mechanical Engineering, Sungkyunkwan University, Suwon, Korea.