

## Development of Regenerative Braking Co-operative Control System for Automatic Transmission-based Hybrid Electric Vehicle using Electronic Wedge Brake

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### Abstract

This research proposes a regenerative braking co-operative control system for the automatic transmission (AT)-based hybrid electric vehicle (HEV). The brake system of the subject HEV consists of the regenerative braking and the electronic wedge brake (EWB) friction braking for the front wheel, and the hydraulic friction braking for the rear wheel. A regenerative braking co-operative control algorithm is suggested for the regenerative braking and friction braking, which distributes the braking torque according to the driver's demand. A vehicle test was performed to evaluate the proposed braking system and co-operative control algorithm.

*Keyword : Regenerative braking, Electronic wedge brake(EWB), Co-operative control, Hybrid electric vehicles*

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### 1 Introduction

In hybrid electric vehicle's (HEV) braking, the regenerative braking can not be used only by itself due to the following reasons: 1) the regenerative braking force is not large enough to cover the driver's demanded braking force, 2) battery state of charge (SOC) limitation, 3) vehicle (motor) speed, etc [1][2]. Therefore, friction braking should be needed together with the regenerative braking and a control algorithm is required to ensure active co-operative control between the regenerative braking and friction braking[3][4].

This study proposes a co-operative control system of the regenerative braking for an automatic transmission (AT)-based HEV using the electronic wedge brake (EWB) on the front wheel, and the hydraulic brake on the rear wheel.

In addition, a regenerative braking co-operative control algorithm is suggested for the regenerative braking and friction braking. A vehicle test was performed to evaluate the proposed braking system and co-operative control algorithm.

### 2 Regenerative braking system for AT-based HEV

Figure 1 shows the regenerative braking system for the AT-based HEV in this study. The HEV is a front-wheel drive vehicle and performs regenerative and friction braking for front wheels and friction braking for rear wheels. The front wheels have a EWB, and the rear wheels, a hydraulic brake. The EWB that is used in this study generates a clamping force by using the self-reinforcing effect on the screw and wedge. This self-reinforcing effect can provide the much

braking force with small actuator power[5]. The hydraulic brake of the rear wheels operates as follows: when a driver steps on the pedal and pushes the piston of the master cylinder, a pressure is formed in the master cylinder. This pressure is supplied to the rear wheel caliper through the hydraulic line and a clamping force is generated. Brake control unit (BCU) distributes the braking force to the front and rear wheel according to the driver's demand and the vehicle condition. The hybrid control unit (HCU) determines the amount of regenerative braking torque using the BCU signals and the gear shift information.

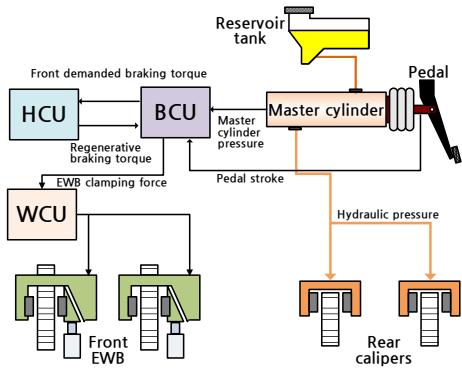


Figure 1 Regenerative braking co-operative control system for AT-based HEV

### 3 Regenerative braking co-operative control algorithm

Figure 2 shows the proposed regenerative braking co-operative control algorithm of this study. The subject vehicle of the study performs the rear friction braking at all section (S, T) through the master cylinder by the driver's brake pedal effort. The regenerative braking on the front wheel and the friction braking on the rear wheel are performed in the section S according to the co-operative control algorithm. The regenerative braking and the friction braking on the front wheel, and the friction braking on the rear wheel operate simultaneously in section T where the demanded deceleration is larger than deceleration of section S.

Figure 3 shows the characteristic map of the drive motor that is installed in the target vehicle. The maximum regenerative braking torque remains the same under the base rpm and decreases when the speed increases. Therefore, the amount of regenerative braking is determined as follows : When the motor speed is  $\omega_A$ , if the front required braking torque (A) is smaller than the maximum regenerative braking torque (B),

the front wheel braking is performed only by the regenerative braking. At the motor speed of  $\omega_B$ , since the maximum regenerative braking torque (C) is smaller than the front required braking torque (A) and the required braking torque cannot be supplied with only regenerative braking, the insufficient braking torque for the front wheel braking is supplemented with friction braking. Thus, even for the braking in Section S in Figure 2, the regenerative and friction braking on the front wheels and the friction braking on the rear wheels may be performed depending on the motor speed. By the same principle, only the regenerative braking on the front wheels and the friction braking on the rear wheels may be performed in Section T.

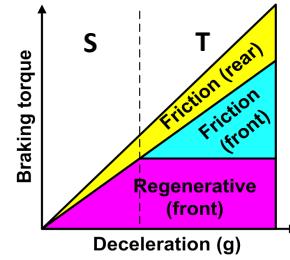


Figure 2 Regenerative braking co-operative control algorithm

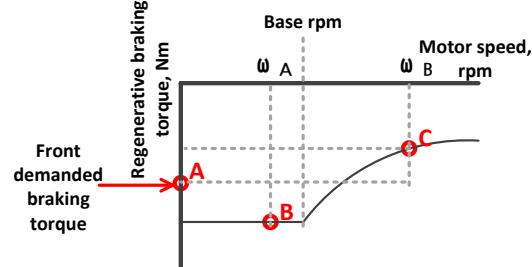


Figure 3 Motor characteristic map

### 4 Vehicle test

To evaluate the performance of the proposed regenerative braking co-operative control system, a vehicle test was performed with an AT-based HEV equipped with the developed braking system(Figure 1). Figure 4 shows a schematic diagram of regenerative braking co-operative control algorithm composed with MATLAB Simulink was installed in the host PC which used DSP (digital signal processor) and CAN I/O to play the role of BCU.

When the driver steps on the brake pedal, the pedal stroke and the pressure of the rear-wheel master cylinder are measured and sent to the BCU, and the braking pressure generated from the rear-wheel

master cylinder pushes the piston of the rear-wheel caliper to generate friction braking force for rear wheels. The BCU determines the total demanded braking torque according to the pedal stroke and calculates the front demanded braking torque considering the pressure of the rear-wheel master cylinder. The front demanded braking torque is input to the HCU and the HCU determines the regenerative braking torque using the vehicle condition and sends it to the vehicle and the BCU. The BCU converts the front demanded braking torque minus the regenerative braking torque to the demanded clamping force of the EWB at the front wheel and sends it to the wedge control unit (WCU) which makes the EWB generate a clamping force according to the demanded clamping force.

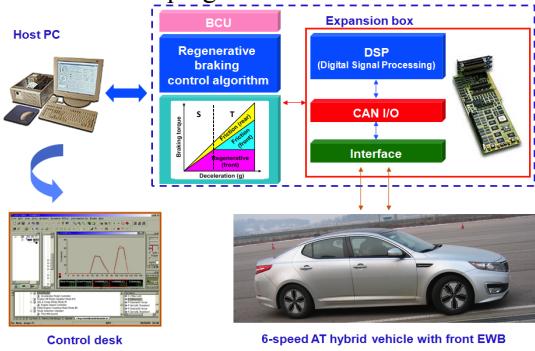


Figure 4 Schematic diagram of regenerative braking co-operative control system for target vehicle

## 5 Experiment results and discussion

The performance of the regenerative braking co-operative control system was evaluated for the deceleration braking of 0.3g starting from  $v=100$  km/h.

Figure 5 shows the experimental results of the regenerative braking co-operative control algorithm. The braking pedal stroke (b) starts to increase at  $t=0.5$  sec and is maintained constant at 36 mm. The pressure of the master cylinder starts to increase together with the braking pedal stroke and is maintained constant at 6 bars. The vehicle velocity (a) begins to decrease from 100 km/h and becomes zero at 9.5 seconds. The automatic transmission gear (c) is at the 5th during the driving and when the braking begins, the gear is downshifted to 4th and 3rd and maintains the 1st after stopping of the vehicle. The front demanded braking torque (d) increases in proportion to the braking pedal stroke and stays constant at 1812 Nm. The regenerative braking torque (d) starts to increase in section O

and increases in section P according to the motor characteristic curve and the automatic transmission gear stage, and becomes constant in section Q. In section N, regenerative braking torque is not generated because it takes time for HCU to calculate the regenerative braking torque after checking the transmission gear stage, the battery SOC and vehicle conditions. Instead, the EWB clamping force (e) increases to fill the insufficient front demanded braking torque in section N because there is no regenerative braking torque. The EWB clamping force increases in section O and decreases in section P as the regenerative braking torque increases. In section Q, the EWB clamping force is constant because the regenerative braking torque is constant. The rear friction braking torque (d) is generated in section N and increases before staying constant at 205 Nm. The deceleration (f) increases in the negative direction as the braking pedal stroke increases, before staying constant at 0.3g.

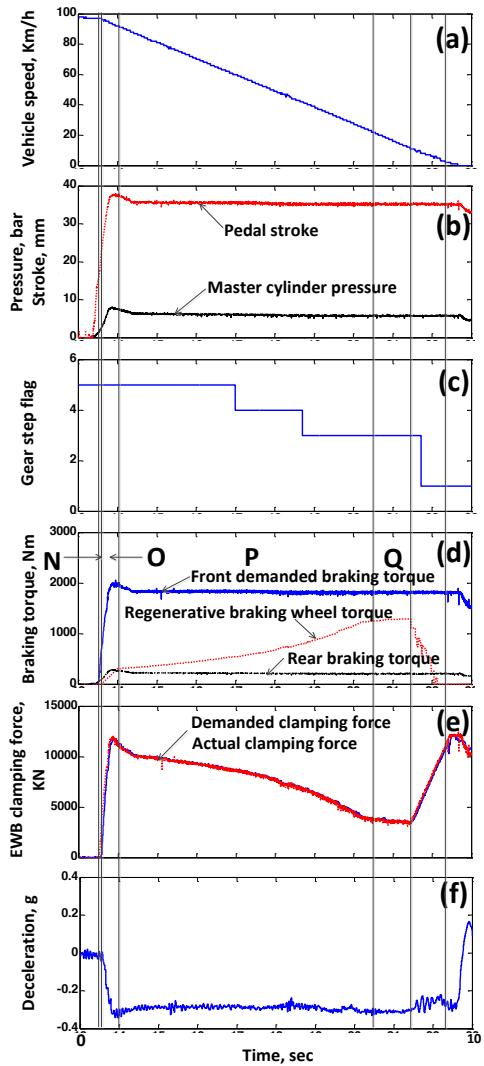


Figure 5 Experimental result (deceleration=0.3g)

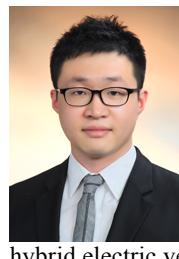
## 6 Conclusion

This study proposed a regenerative braking co-operative control system which consists of EWB friction braking for front wheels and hydraulic friction braking for rear wheels. A co-operative control algorithm was suggested for the regenerative braking and friction braking, which distributes the braking torque according to the driver's demand. A vehicle test was performed to evaluate the proposed braking system and co-operative control algorithm. The results of the experiment show that the rear wheel braking was operated at all times through the master cylinder by the driver's brake pedal effort, and the front wheel braking were performed by the regenerative braking and EWB friction braking according to the co-operative control algorithm. The driver's demand for the braking force was satisfied through the co-operative control of the regenerative and friction braking.

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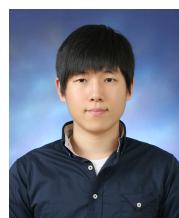
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