

A Study on Regenerative Braking for a Parallel Hybrid Electric Vehicle

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In this paper, a regenerative braking algorithm is presented and performance of a hybrid electric vehicle (HEV) is investigated. The regenerative braking algorithm calculates the available regenerative braking torque by considering the motor characteristics, the battery SOC and the CVT speed ratio. When the regenerative braking and the friction braking are applied simultaneously, the friction braking torque corresponding to the regenerative braking should be reduced by decreasing the hydraulic pressure at the front wheel. To implement the regenerative braking algorithm, a hydraulic braking module is designed. In addition, the HEV powertrain models including the internal combustion engine, electric motor, battery, CVT and the regenerative braking system are obtained using AMESim, and the regenerative braking performance is investigated by the simulation. Simulation results show that the proposed regenerative braking algorithm contributes to increasing the battery SOC which results in the improved fuel economy. To verify the regenerative braking algorithm, an experimental study is performed. It is found from the experimental results that the regenerative braking hydraulic module developed in this study generates the desired front wheel hydraulic pressure specified by the regenerative braking control algorithm.

Key Words : HEV, Regenerative Braking, CVT

1. Introduction

In a regenerative braking, kinetic energy of the vehicle is stored in an energy storing device instead of being dissipated and the stored energy is used to drive the vehicle later on. In a hybrid electric vehicle (HEV), energy recuperation takes

place by transforming the mechanical energy into the electrical energy via a generator. The electrical energy stored in a battery is used to propel the vehicle via a motor. By doing so, a significant improvement of the fuel economy can be achieved. Studies in the past suggest that an HEV's range for in-city driving can be extended between 14 and 40% by using the regenerative braking (Laplante, J., 1995, Triger, L., 1993).

Generally, the regenerative braking system works together with conventional friction brake for the following reasons : (1) the regenerative braking torque is not large enough to meet the required braking torque, (2) the regenerative

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braking can not take place when the battery state of charge (SOC) is above the upper limit to protect the battery. In these cases, the conventional friction brake supply the required braking torque. Therefore, in order to apply the regenerative braking, a control algorithm on how to divide the braking torque into the regenerative torque and the friction torque is required with respect to the battery SOC, motor speed and etc. It is also important to provide a brake feeling that is similar to that of the conventional braking during the regenerative braking. Since Toyota introduced a parallel HEV, 「Prius」equipped with the regenerative braking, in 1997, Honda has followed. In addition, big three introduced HEV concept cars under PNGV program. However, only a few works have been reported on the regenerative braking. As for the regenerative braking of the electric vehicle (EV), Wyczalk (F. A. Wyczalk, 1992) showed that energy storage can be achieved for the city driving mode by 20% and for the rural driving mode by 6% by adopting the regenerative braking. Bailey(K. E. Bailey, 1996) suggested a regenerative braking algorithm for the EV from the viewpoint of stability by considering the proportioning of the hydraulic pressure to the front and the rear wheel. Chun (Chun B. J., 1996) suggested a regenerative braking algorithm, which increases or decreases a frictional braking force in proportion to the regenerative braking requirement. In Toyota's Prius, an electronically controlled regenerative braking system is introduced for a parallel HEV using 30kW motor (Prius Manual, 1997). The hydraulic module in the brake system consists of an ingeniously designed master cylinder, and a stroke simulator to absorb the brake oil flow. Panagiotidis et. al. (Panagiotidis, M., 2000) suggested a regenerative braking model for a parallel HEV using ADVISOR. This model computes the wheel pressure, based on a look-up table yielding the distribution of brake forces between the front and rear wheel and the generator. However, a detailed modeling of the regenerative braking system is not considered.

In this paper, a regenerative braking control algorithm is presented for a parallel HEV

equipped with a continuously variable transmission (CVT) and a hydraulic module is designed to implement the proposed control algorithm. In addition, a regenerative braking simulator is developed based on the dynamic models of the HEV powertrain including the brake system, and performance of the regenerative braking is investigated.

2. Regenerative Braking Algorithm

Figure 1 shows a schematic diagram of the parallel HEV used in this study. Engine is connected with a motor by a single shaft. One clutch is used between the motor and the transmission. As a transmission, a metal belt CVT is used to maintain the engine operation on the minimum fuel consumption region independent of the vehicle speed. The HEV used in this study adopts a front-wheel drive.

In order to provide an appropriate regenerative braking (REGEN) for given driving conditions, a control algorithm is required to determine the magnitude of the regenerative torque with respect to the battery SOC, motor speed and the driver's demand.

Figure 2 shows a motor characteristic curve

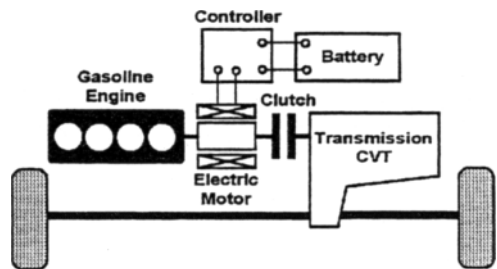


Fig. 1 Schematic diagram of parallel HEV

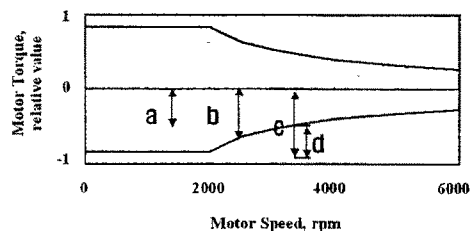


Fig. 2 Motor torque characteristics

used in this study. Negative torque means the regenerative torque that the motor is able to generate. If the required braking torque is “a”, the front wheel braking can be achieved only by the REGEN since “a” is smaller than the available motor torque. When the driver needs the torque, “c” which is larger than the available motor torque, the conventional friction brake has to be operated to supply the insufficient torque, “d”. Therefore, the total braking torque T_B is represented as,

$$T_B = T_R + T_F \tag{1}$$

where T_R is the regenerative torque and, T_F is the friction torque which is applied to the wheel.

In the HEV in Fig. 1, the front wheel braking is performed by the REGEN plus the friction brake meanwhile the rear wheel is under purely the friction braking. The REGEN torque applied to the front wheel, T_{REGf} is represented as,

$$T_{REGf} = i \cdot N_d \cdot T_{REGmotor} \tag{2}$$

where i is the CVT speed ratio, N_d is the final reduction gear ratio and, $T_{REGmotor}$ is the regenerative torque by the motor. When the REGEN and the friction braking work together, the hydraulic pressure corresponding to the regenerative torque should be reduced as follows:

$$\Delta P = \frac{T_{REGf}}{A_{wcf} \times \mu \times 2 \times r} \tag{3}$$

where μ is the friction coefficient, A_{wcf} is the front wheel cylinder area and, r is the effective radius. Therefore, the hydraulic pressure P_f^* which needs to be supplied to the front wheel yields

$$P_f^* = P_m - \Delta P \tag{4}$$

where P_m is the master cylinder pressure.

In Fig. 3, an algorithm to determine magnitude of the regenerative torque is shown. If the available regenerative torque T_{REGf} is less than the desired front braking torque T_f^* , the difference torque, $T_f^* - T_{REGf}$ should be provided by the friction braking, and the front wheel pressure which is reduced by the amount of ΔP is applied. If T_{REGf} is larger than T_f^* , the front wheel braking is obtained only by the REGEN and no

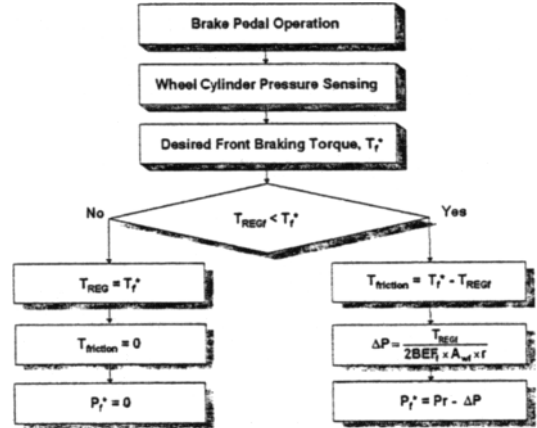


Fig. 3 Flow chart for regenerative braking

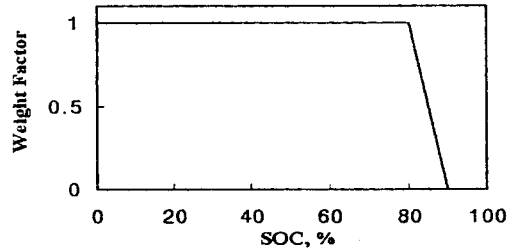


Fig. 4 Weight factor for regenerative braking

friction braking is required, which results in zero front wheel pressure.

In addition, in determining the REGEN torque, the battery SOC should be considered. In this study, the REGEN torque is obtained by multiplying the weight factor WF which is a function of the battery SOC (Fig. 4).

3. Regenerative Hydraulic Module

In order to implement the REGEN algorithm described previously, the REGEN system has to have the following capabilities:

- measure the master cylinder pressure which is directly related to the driver’s demand.
- calculate the regenerative torque
- calculate the available motor torque by considering the battery SOC, motor speed and CVT ratio
- provide familiar brake pedal feeling when the REGEN is performed

Figure 5 shows a schematic diagram of the

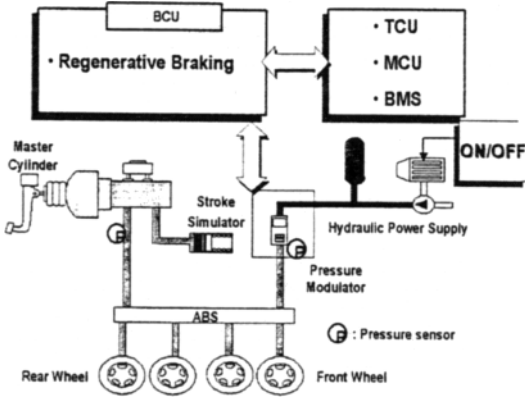


Fig. 5 Regenerative braking system

REGEN hydraulic module which is developed in this study to meet the above design specifications. The REGEN system in Fig. 5 consists of a booster, a master cylinder, a stroke simulator, a pressure modulator and a hydraulic power unit. A vacuum booster operated by the engine is used since the engine used in this study is always running in the drive mode. The pressure modulator controls the front wheel pressure according to the REGEN algorithm. When the REGEN works, the pressure modulator supplies the front wheel pressure which is reduced by ΔP from Eq. (3). The accumulator pressure is controlled to maintain the pressure between 100 bars and 120 bars. When the accumulator pressure exceeds the upper limit, the motor turns off and vice versa. This motor on-off operation keeps the motor from wasting unnecessary power. The stroke simulator is used to provide a familiar feeling of the brake pedal. When the REGEN is carried out, the oil flow to the front wheel is shut off or is reduced, which causes a strange pedal feeling to the driver. Therefore, the stroke simulator is installed to waste the oil flow corresponding to the brake pedal stroke.

4. Powertrain Modeling

Vehicle Dynamics : State equation of the HEV velocity when the engine and the motor work together is represented as,

$$\frac{dV}{dt} = \frac{i \frac{N_d}{R_t} (T_e + T_m) - F_L - F_b - \frac{N^2 i \frac{di}{dt} J}{R_t^2} V}{M + \left(\frac{i N_d}{R_t}\right)^2 J} \quad (5)$$

where T_e is the engine torque, T_m is the motor torque, F_L is the road load, F_b is the brake force, R_t is the tire radius, M is the vehicle mass and, J is the vehicle inertia.

Engine : Since the engine and the motor is connected, state equation of the engine is expressed as,

$$(J_e + J_m) \frac{d\omega_e}{dt} = T_e + T_n - T_{loss} - T_{net} \quad (6)$$

where J_e, J_m are the engine and the motor inertia, respectively, ω_e is the engine speed, T_{loss} is the auxiliary device loss, T_{net} is the CVT input torque.

Motor : The motor is used as a tractive effort when the battery is discharged and is used as a generator when the battery is charged, in other words, in the regenerative braking mode. When the motor is used as a tractive effort, the motor torque T_m is represented as

$$T_m = K_t I \quad (7)$$

where K_t is the motor torque constant and, I is the current. The motor torque transmitted to the wheel can be obtained including the motor efficiency.

Battery : The battery SOC is represented as follows:

$$SOC = SOC_0 - \frac{B_c \Delta t}{3600 B_F} \quad (8)$$

where SOC_0 is the battery initial SOC [%], B_c is the consumed power [kW], B_F is the full charge power [kW] and, Δt is the sampling time.

CVT : The CVT shift dynamics plays an integral role in the vehicle response. In addition, the CVT shift dynamics affects the engine performance on the optimal operation line (OOL). For instance, the faster the CVT shift speed becomes, the closer the engine can be operated on the OOL. In this study, the following CVT shift dynamics suggested by Ide (Ide, T., 1996) is used.

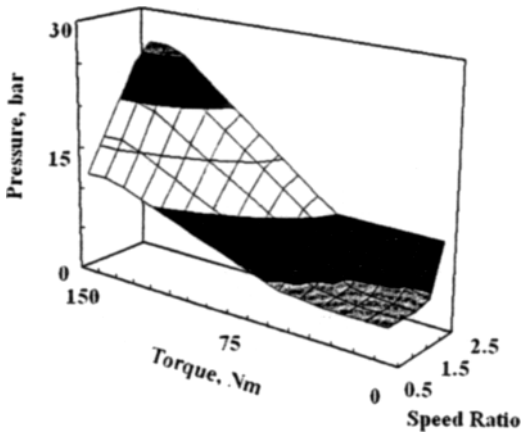


Fig. 6 3-D map of CVT speed ratio-torque-line pressure

$$\frac{di}{dt} = \beta(i) \omega_p (F_p - F_p^*) \quad (9)$$

where $\beta(i)$ is the constant which is a function of the CVT ratio i , ω_p is the primary pulley speed, F_p is the primary thrust and, F_p^* is the primary thrust at a steady state. The CVT ratio needs to be controlled to move the engine operation point on the optimal operation line (OOL) for the best fuel economy. The desired CVT ratio i_d is defined as:

$$i_d = \frac{R_t \omega_d}{N_d V} \quad (10)$$

where ω_d is the desired engine speed which can be obtained as a point where the OOL and the throttle valve opening curve cross each other (Kim, H. S., Song, H. L., 1996).

In the CVT, power is transmitted via friction between the belt and the pulley. In order to prevent the belt from slippage, a sufficient belt clamping force, in other words, line pressure is required. However, the excessive line pressure causes a hydraulic power loss as well as a short fatigue life of the belt. Therefore, it is required to supply an optimal line pressure for the given torque and the speed ratio. Figure 6 shows a 3-D line pressure map used in the simulation. The line pressure map in Fig. 6 is obtained from the experiments (Kim, H. S., Kim, T. C., 2000).

REGEN hydraulic system : In Fig. 7, the REGEN hydraulic system is modeled using

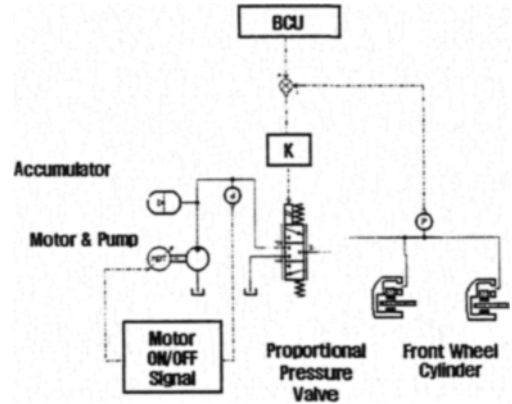


Fig. 7 Regenerative hydraulic module

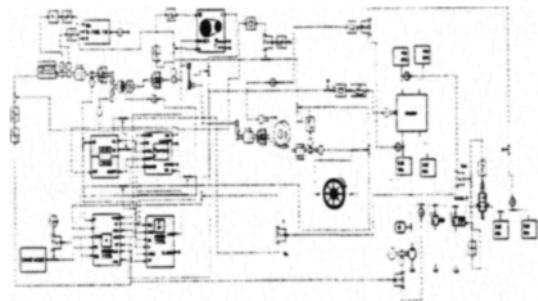


Fig. 8 HEV REGEN simulator

AMESim(advanced modeling environment for performing simulation of engineering) software (Marc Alirand, Fabrice Gallo, 1999). AMESim has many advantages in modeling the hydraulic system and in combining the other dynamic systems. In Fig. 7, a proportional pressure reducing valve is used to modulate the front wheel pressure. The reducing valve is operated by the control signal from BCU (brake control unit).

Based on the dynamic models of the powertrain, a HEV simulator is developed. Figure 8 shows AMESim model of the HEV simulator including the REGEN system model developed in this study.

5. Simulation Results and Discussion

In Table 1, vehicle parameters used in the simulation are shown. Figure 9 shows the simulation results of the HEV regenerative braking performance when the HEV is

Table 1 Vehicle data

Engine		
Stroke volume	(V_s)	1600cc
Maximum torque	(T_e)	140Nm
Motor		
Motor torque at 0rpm		50Nm
Peak power		10kW
CVT-Differential Gear		
CVT gear ratio range	(i)	0.455~2.47
Final reduction gear ratio	(N_d)	5.763
Car body		
Vehicle mass	(m)	1380kg
Front project area	(A)	1.964m ²
Drag coefficient	(C_d)	0.346
Tire radius	(R_t)	0.279m

decelerated from 40KPH to 0KPH in 10 seconds. The drive mode(a) consists of an acceleration, 40KPH cruising and a deceleration. The vehicle velocity follows closely the driving mode. The CVT speed ratio(b) maintains the highest gear ratio $i=0.45$ at 40KPH and begins to downshift when the deceleration starts, and the CVT ratio shows a drive-off gear ratio at $V=0$ KPH. The engine speed(c) decreases to the idling speed during the braking. The brake pedal(e) is depressed by 20% to decelerate the vehicle. (f) shows the friction brake torque (a) by the rear wheel and the available regenerative torque(b) by the motor.

Since it is assumed that the front wheel hydraulic pressure is equal to the rear wheel pressure by neglecting the brake pressure proportioning when the REGEN does not work, the difference torque between (a) and (b) needs to be applied to the front wheel by the conventional friction brake. (g) is the reduction pressure ΔP corresponding to the regenerative torque(b). Therefore, in the front wheel, the hydraulic pressure reduced by the amount of ΔP is applied. As show in (h), the front wheel pressure P_f decreases to 0bar and maintains 0bar until the braking is completed. During this period, the front wheel braking is carried out only by the REGEN. The motor torque shows a positive value when it is used as the tractive effort and shows a negative value during the REGEN. The battery SOC decreases from the initial SOC, 50% while the motor assists the engine to propel the vehicle and increases during the REGEN. The hydraulic motor power(k) required to operate the brake system is 0.3kW, which is consumed in the initial stage of the vehicle acceleration to build the accumulator pressure up to 120 bars. The accumulator pressure decreases to 105bars during the braking.

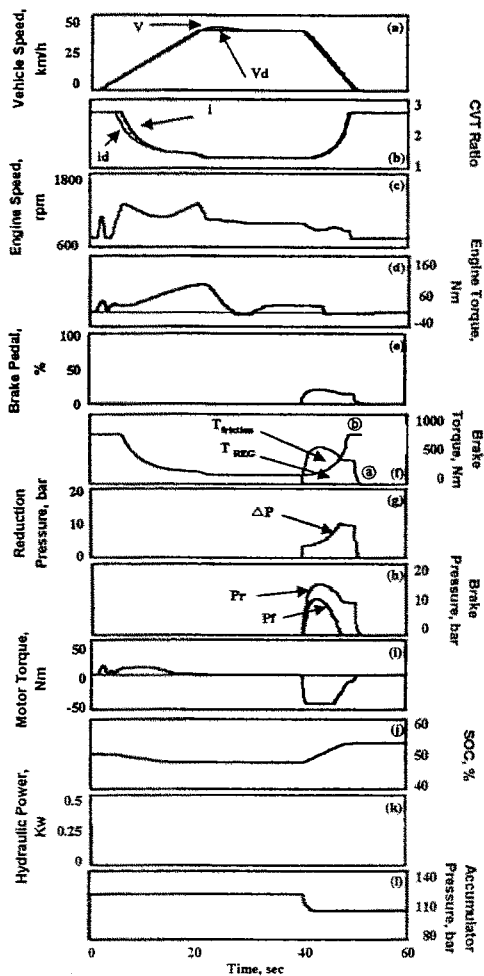


Fig. 9 Simulation results ($V_{max}=40$ KPH)

Figure 10 shows the simulation results when the HEV is decelerated from 80KPH to 0KPH in 10seconds. The vehicle velocity(a) follows the drive mode closely. The CVT ratio(b), engine speed(c) and the engine torque(d) show similar trends with those of 40KPH deceleration (Fig. 10). The brake pedal(e) is depressed by 50%. (f)

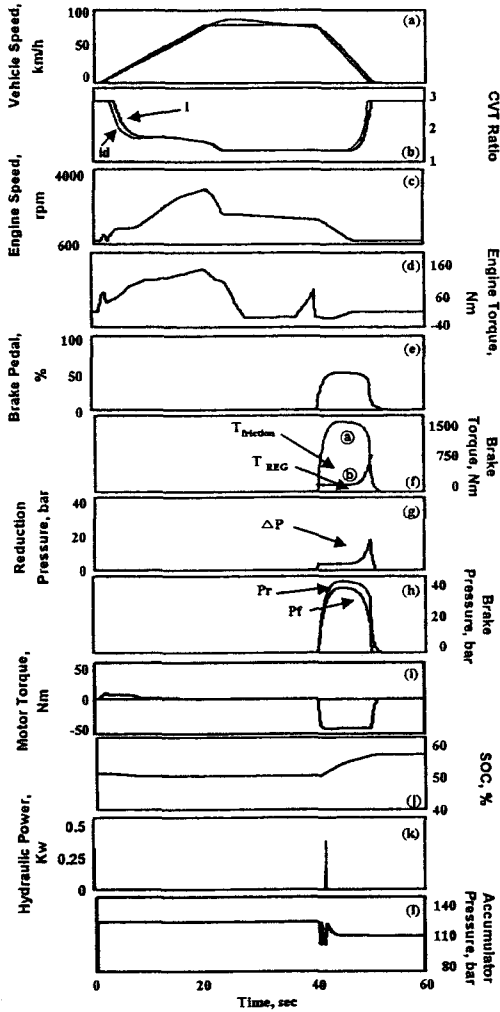


Fig. 10 Simulation results ($V_{max}=80\text{KPH}$)

shows the friction brake torque[Ⓐ] and the available regenerative motor torque[Ⓑ]. Therefore, in the front wheel, the difference torque [Ⓐ]-[Ⓑ] should be supplied by the conventional friction brake together with the regenerative torque[Ⓒ]. As shown in (h), the front wheel hydraulic pressure, which is reduced by ΔP is applied^(g) corresponding to the regenerative torque. During the deceleration, the motor torque⁽ⁱ⁾ shows a negative value, and correspondingly, the battery SOC^(j) increases. From (k), it is seen that the hydraulic motor power is consumed again to build up the accumulator pressure when the hydraulic pressure decreases below 100bars^(l).

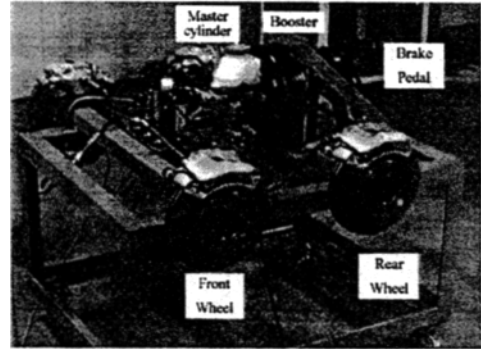


Fig. 11 Regenerative brake tester

It is noted from the simulation results in Figs. 9 and 10 that the REGEN is carried out according to the braking control algorithm proposed in this study and contributes to increase the battery SOC which results in an improved fuel economy.

6. Experiment on Regenerative Braking Pressure

Figure 11 shows the experimental apparatus. The aim of the experiment is focused on performance of the REGEN hydraulic system developed in this study. Therefore, all the hardwares except the hydraulic brake system are replaced by the software models and it is assumed that the REGEN is achieved by the reduced pressure ΔP . In the experiments, the BCU determines the front wheel pressure according to the control algorithm, and the front wheel pressure is supplied via the pressure reducing valve by reducing the rear wheel pressure by the amount of ΔP .

Figure 12 shows the experimental results for 80KPH deceleration. For the convenience of the experiments, deceleration time is set to be 17seconds. The rear wheel pressure P_r , front wheel pressure P_f and ΔP are shown in (a). In the beginning stage of the braking, P_f does not increase in spite of the increased P_r because the front wheel braking is performed only by the REGEN. ΔP increases after showing almost constant value and remains around 20bars, which is equivalent to the available regenerative motor torque. In the following period, P_f follows P_r showing the pressure difference ΔP . When P_f

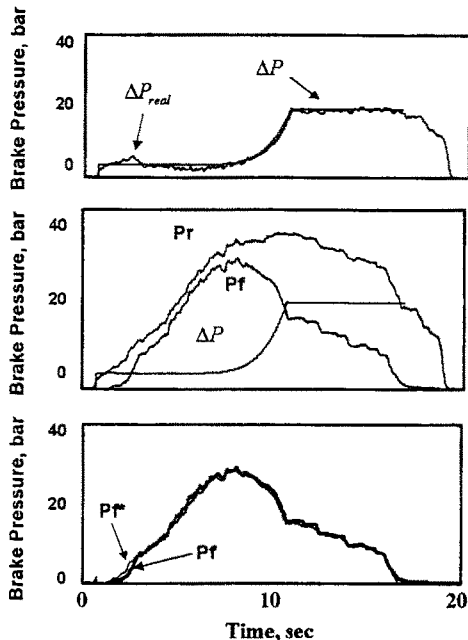


Fig. 12 Experimental results

becomes lower than ΔP , the front wheel pressure shows 0bar, which means that only the REGEN is carried out in the front wheel. (b) and (c) show comparison of the actual pressure and the target pressure. It is seen from (b) and (c) that actual P_r and ΔP follow the target pressures according to the control algorithm proposed in this study.

It is found from the experimental results that the REGEN hydraulic module developed in this study generates the front wheel hydraulic pressure according to the REGEN control algorithm.

7. Conclusion

A regenerative braking algorithm is presented for a parallel hybrid electric vehicle (HEV). The control algorithm determines the regenerative torque by considering the motor speed, battery SOC and the CVT speed ratio. In order to realize the control algorithm, a regenerative braking hydraulic module is developed. The hydraulic module supplies the front wheel pressure by reducing the rear wheel pressure by ΔP corresponding to the regenerative torque. The torque difference between the rear wheel and the

regenerative motor torque needs to be supplied by the conventional friction brake. In addition, a HEV performance simulator is developed using AMESim based on the dynamic models of the HEV powertrain including the motor, battery, CVT and the regenerative braking hydraulic module. The simulation results show that the regenerative braking is carried out according to the braking control algorithm suggested in this study and contributes to increase the battery SOC which results in a improved fuel economy. It is found from the experimental results that the regenerative braking hydraulic module developed in this study generates the front wheel hydraulic pressure according to the regenerative braking control algorithm.

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