Regenerative Braking Control Algorithm for an Electrified Vehicle Equipped with a By-Wire Brake System

2014-01-1791
Published 04/01/2014

Chen Lv, Junzhi Zhang, Yutong Li, and Ye Yuan
State Key Lab of ASE, Tsinghua Univ.

CITATION: Lv, C., Zhang, J., Li, Y., and Yuan, Y., "Regenerative Braking Control Algorithm for an Electrified Vehicle Equipped with a By-Wire Brake System," SAE Technical Paper 2014-01-1791, 2014, doi:10.4271/2014-01-1791.

Abstract

Regenerative braking, which can effectively improve vehicle's fuel economy by recuperating the kinetic energy during deceleration processes, has been applied in various types of electrified vehicle as one of its key technologies. To achieve high regeneration efficiency and also guarantee vehicle's brake safety, the regenerative brake should be coordinated with the mechanical brake. Therefore, the regenerative braking control performance can be significantly affected by the structure of mechanical braking system and the brake blending control strategy.

By-wire brake system, which mechanically decouples the brake pedal from the hydraulic brake circuits, can make the braking force modulation more flexible. Moreover, its inherent characteristic of 'pedal-decouple' makes it well suited for the implementation in the cooperative regenerative braking control of electrified vehicles.

With the aims of regeneration efficiency and braking performance, a regenerative braking control algorithm for electrified vehicles equipped with a brake-by-wire system is researched in this paper. The layout of the adopted brake-by-wire system is introduced. The proposed regenerative braking control algorithm is illustrated. To validate the control performance of the algorithm, hardware-in-the-loop simulations are carried out. The simulation results show that, based on brake-by-wire system, the proposed control algorithm, coordinating regenerative brake and hydraulic brake well, can further improving the regeneration efficiency of electrified vehicle and guarantee the braking performance in the meantime.

Introduction

The ever heavier burden on the environment and energy requires automobiles to be cleaner and more efficient. Studies show that, in urban driving situations, about one third to one half of the energy of the power plant is consumed during braking [1, 2, 3, 4, 5]. Among the key features of electric vehicles, regenerative braking system (RBS) offers the capability to improve the fuel economy effectively by converting vehicle's kinetic energy into electric energy during deceleration processes. It has become a key topic of research and development among automotive makers, component suppliers, and research institutes worldwide.

Most of the commercialized electrified vehicles now are equipped with a regenerative braking system. However, to guarantee the vehicle's brake performance, a mechanical brake is still needed. Since the regenerative braking force and the friction braking force are coordinated during the deceleration processes, the brake blending performance can be significantly affected by the mechanical braking system and the regenerative braking control strategy [2]. Therefore, researching the effective control strategy based on an appropriate brake system is of great necessity and importance.

To keep the blended braking force consistent with driver's braking request and maximize the regeneration efficiency, the friction braking force needs to be regulated cooperatively in real-time based on the variation of the regenerative braking force provided by the electrified powertrain. However, in a conventional brake system, the brake pedal is mechanically connected to the hydraulic brake circuit, resulting in the brake pedal feel being affected by hydraulic pressure modulation during brake blending. Hence, mechanical decoupling of the brake pedal from the hydraulic brake circuit is required in a regenerative braking system of an electrified vehicle.

Brake-by-wire system, which mechanically decouples the brake pedal from the actuation of the mechanical brake devices, can make the braking force distribution and modulation between the front and the rear axles more flexible [6, 7, 8]. It was initially developed to improve the dynamic performance of conventional ICE vehicles and has been applied in some commercialized cars. However, its inherent ‘pedal-decouple’ structure make it well suited for the implementation of the cooperative regenerative braking control.

Automotive makers and component suppliers worldwide have developed several RBS solutions for electrified vehicles based on ‘brake-by-wire’ concept. Toyota developed the ECB (Electronically Controlled Brake) system, which has been brought into series production and implemented successfully in commercialized HEV Prius [9]. Hitachi proposed the EDiB, which has been employed in the pure electric vehicle Nissan Leaf [10]. And Hyundai, Continental, Honda, and Borsch etc. have developed regenerative braking systems for electrified vehicles based on by-wire concept as well [11, 12, 13].

Researchers also have carried out some studies in this area. Ko et al. proposed a cooperative regenerative braking control algorithm for an EV equipped with EWB and EMB [14]. Mi et al. proposed the use of EMB in combination with regenerative braking in PHEV [15].

In order to further explore the potential of the braking energy regeneration of electrified vehicles, this paper presents a regenerative braking control algorithm based on a by-wire brake system. The layout of the adopted brake-by-wire system is introduced. The regenerative braking control algorithm based on brake-by-wire system is proposed. The models of the main components related to the regenerative brake and the frictional brake of the target electric passenger car are built in MATLAB/Simulink. The control effects and regeneration efficiencies of the proposed control strategy are simulated in the hard-ware-in-the-loop test bench. Some simulation results are presented in this article.

Regenerative Braking System Configuration

System Outline

A cooperative regenerative braking system for a front-wheel-drive electric passenger vehicle equipped with a by-wire brake system was designed. The overall structure of the regenerative braking system is shown in Figure 1. An electric control unit, the BCU (Brake Control Unit) is applied in the regenerative braking system. The BCU communicates with VCU (Vehicle Control Unit) and MCU (Motor Control Unit) via CAN bus. The hydraulic actuator of the regenerative braking system developed is a by-wire brake system, which is installed between the master cylinder and the wheel cylinders.

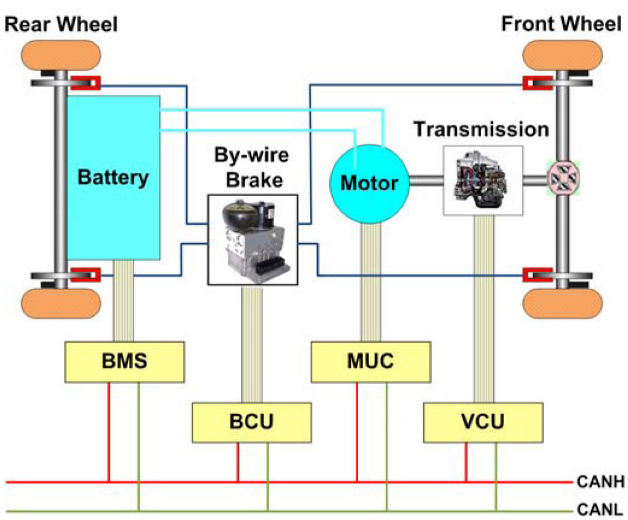

Figure 1. Overall structure of the regenerative braking system.

By-Wire Brake System

As the key component of the proposed regenerative braking system, the by-wire brake system is adopted as the electrohydraulic type, which is comprised of a brake pedal simulator, a high-pressure supply unit, and a hydraulic pressure modulator, as Figure 2 shows. The brake pedal is mechanically decoupled from the brake circuits in the downstream by the brake pedal simulator. The hydraulic pressure in the brake circuits is actually provided by the high-pressure supply unit and regulated by the hydraulic pressure modulator, making the ‘brake-by-wire’ concept realized. Since the pedal force is decoupled, the driver's braking intention is detected by the pedal stroke sensor and sent to BCU. Based on the pedal stroke signal detected and the real-time operating conditions of the electric powertrain, BCU controls the actuations of the hydraulic pressure modulator, regulating the wheel pressure. The modulated wheel cylinder pressure cooperates with the regenerative braking torque provided by the electric motor, realizing the cooperative regeneration based on the by-wire brake system.

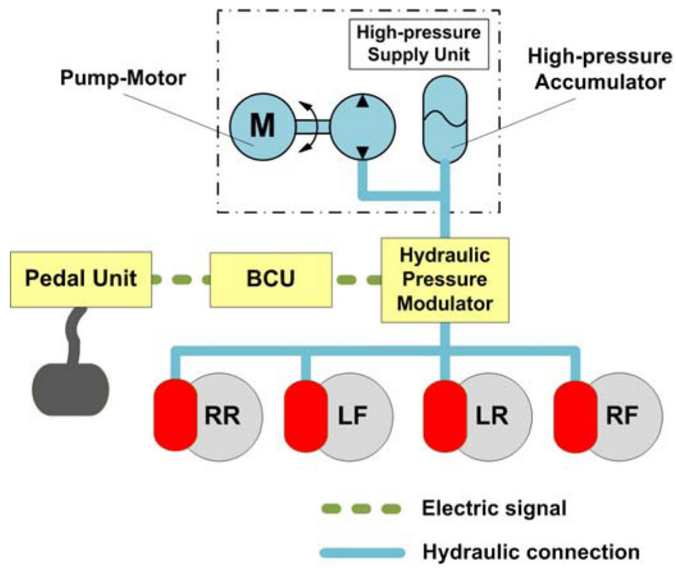

Figure 2. Structure of the by-wire brake system.

By-Wire Brake Based Regenrative Braking Control Algorithm

Braking Force Distribution Strategy

In a conventional vehicle, since the brake pedal is mechanically connected to the downstream of the brake circuits, the front-rear brake force distribution (BFD) is not regulated during braking processes and set as a fixed value, which is determined by parameters of the installed brake devices, to avoid the brake pedal feel not being affected by the modulation of hydraulic pressure. However, for an electrified vehicle equipped with a brake-by-wire system, the brake pedal is mechanically decoupled from the mechanical brake actuators, and the ideal braking distribution can be achieved by the by-wire brake system via modulating the braking forces between the front and the rear wheels. Thus, to achieve high regeneration efficiency and guarantee the brake safety in the meantime, the front-rear brake force distribution needs to be reconsidered.

Front and Rear Braking Force Allocation

For a front-wheel-drive car, the motor's braking torque can be only exerted on the front axle. To reach the maximum regeneration efficiency, the front-axle regenerative braking torque needs to be fully utilized, leading to the BFD being close to the X axis in Figure 3. But to guarantee the stability during braking processes, a vehicle should have enough rear braking force, which is required by the regulation of ECE-R13, as equation (1) and equation (2) show [16].

$$z \geq 0.1 + 0.85(\varphi - 0.2) \tag{1}$$

$$z = \frac{du}{dt} \cdot \frac{1}{g} \tag{2}$$

where, z indicates the brake intensity, φ is the adhesion coefficient of the road, u is the longitudinal velocity of the vehicle.

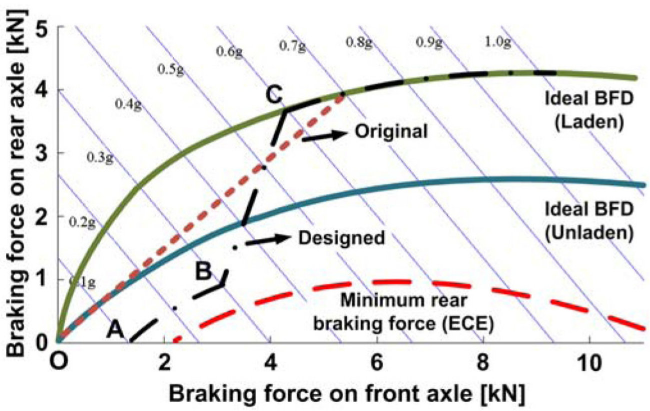

Figure 3. Front and Rear braking force allocation.

However, if the desirable braking performance is expected, the BFD should be set close to the ideal BFD, which is far from the x axis. As the ideal braking force allocation required, the front/rear braking forces can be expressed as [1]:

$$F_{\mu 1} + F_{\mu 2} = \varphi \cdot G \tag{3}$$

$$\frac{F_{\mu 1}}{F_{\mu 2}} = \frac{b + \varphi \cdot h_g}{a - \varphi \cdot h_g} \tag{4}$$

Eliminating the variable φ, the relationship between front-wheel braking force and rear-wheel braking force can be given as equation (5), and the ideal BFDs (laden and unladen) are shown in Figure 3.

$$F_{\mu 2} = \frac{1}{2}\left[\frac{G}{h_g}\sqrt{b^2 + \frac{4h_g L}{G}F_{\mu 1}} - \left(\frac{Gb}{h_g} + 2F_{\mu 1}\right)\right] \tag{5}$$

where, $F_{\mu 1}$ is the front-wheel braking force, 2 $F_{\mu 2}$ is the rear-wheel braking force, G is the gravity of the vehicle, a is the longitudinal distance from the centre of gravity of the vehicle to the front axle, b is the longitudinal distance from the centre of gravity to the rear axle and L is the axle base, h_g is the height of the gravity centre.

Therefore, according to the analysis above, we can see that there exists a contradiction between regeneration efficiency and brake performance in designing the front/rear BFD for a front-wheel-drive electric car. The BFD for maximizing regeneration is required to be far from the one demanded by maximizing braking performance. For the original strategy, the BFD is set as a fixed value [18], i.e., the front brake force is linearly correlated with the rear one, as the red dotted line shown in Figure 3. By doing this, however, the regeneration capability cannot be fully utilized. To tackle with this issue, coordinating the regeneration efficiency and braking performance, a BFD for electric car is worthwhile to be explored.

During the daily operating conditions of an electric vehicle, the regenerative braking usually needs to be activated under normal braking procedures, which is corresponding to the deceleration of the vehicle at 0.1g-0.3g. Once entering the critical braking situations (deceleration of the vehicle is usually greater than 0.5g), a good braking performance is required for a vehicle to ensure a short braking distance. Based on these practical requirements of a vehicle introduced above, targeting on a front-wheel-drive electric car, a braking force distribution strategy is proposed as follows:

1. As shown in Figure 3, under small brake intensity, only front-wheel regenerative braking force is applied to, and no friction brake on rear axle is exerted (O to A);
2. To fully guarantee the rear braking force is within the requirement of the ECE regulation, the rear-wheel friction force starts to be added and modulated by the by-wire brake system from point A, before reaching the limitation required by the ECE regulation;
3. When the deceleration is beyond 0.3g, the designed line of BFD gets close to the ideal BFD (B to C) gradually, to make the vehicle obtain a better braking performance under heavier brake intensity;
4. Once the deceleration reaching 0.6g (C point), the vehicle enters the emergency driving condition, and the by-wire brake system will regulate the hydraulic forces in front and rear wheels, making the designed BFD go complying with the ideal one, guaranteeing the best dynamic braking performance of the vehicle.

The designed BFD is illustrated in Figure 3, as the black dotted line shows. Based on the regenerative braking control strategy described above, the target electric vehicle can be expected to achieve the high regeneration efficiency under normal deceleration processes, and ensure the good braking stability under emergency braking situations.

Regenerative and Hydraulic Brakes Distribution

As shown in Figure 4, during deceleration, the overall braking force of the vehicle is supplied by the regenerative and the friction blending brakes. The overall brake force is controlled being consistent with the brake intention of the driver, as equation (6) shows.

$$T_{b\_need} = T_{reg} + T_{fric} \tag{6}$$

where, T_{b_need} is the total braking demand of the vehicle, T_{reg} is the regenerative braking torque generated by the electric motor, T_{fric} indicates the friction braking torque provided by the mechanical braking system.

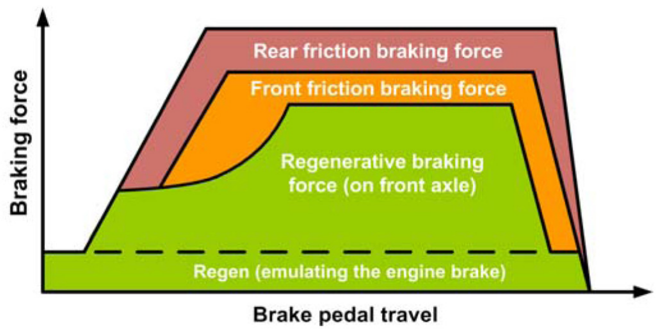

Figure 4. Distribution between regenerative brake and hydraulic brake.

To maximize the regeneration efficiency, during brake blending, the regenerative braking torque is fully used on the front axle. As shown in Figure 4, only regenerative brake is exerted on front axle at first. Based on the control algorithm, once the brake request cannot be met solely by the electric brake, the rear-wheel hydraulic brake will be supplemented by the by-wire brake system. And with the increase of the driver's brake demand, the hydraulic braking force on the front axle will then be applied gradually. In addition, when the car enters any critical driving situations, such as the anti-lock braking system (ABS) or the traction control system (TCS) activates, the regenerative braking torque will be removed gradually, i.e. only the hydraulic brake takes over all the braking operation under emergency braking conditions.

Control Algorithm of the Cooperative Regenerative Braking

Figure 5 illustrates the control block diagram of the cooperative regenerative braking. When the driver depresses the brake pedal, the total brake demand (T_{b_need}) can be detected via pressure sensor in the pedal unit, as equation (7) shows.

$$T_{b\_need} = \frac{4\pi \cdot \mu_b r_f^2 R_{e\_f}}{\beta} \cdot p_m \tag{7}$$

where, p_m is the hydraulic cylinder pressure of the pedal unit, μ_b is the friction coefficient of the brake disc, r_f is the radius of the piston of the front wheel cylinder, R_{e_f} is the effective friction radius of the brake disc and β is the real-time front-rear braking force distribution coefficient.

Based on the brake demand of the vehicle and the designed braking force distribution strategy, the front-axle braking torque (T_{b_f}) and rear-axle braking torque (T_{b_r}) can be calculated as follows:

$$T_{b\_f} = 4\pi \cdot \mu_b r_f^2 R_{e\_f} \cdot p_m \tag{8}$$

$$T_{b\_r} = T_{b\_need} - T_{b\_f} \tag{9}$$

As equation (10) shows, according to the SOC of the battery pack, the speed of the motor, and the torque demand of the front axle, BCU calculates the command value of the regenerative braking torque (T_{reg_cmd}) and send it to MCU via CAN bus.

$$T_{reg\_cmd} = \min(T_{reg\_\lim}, T_{b\_f}) \tag{10}$$

where, T_{reg_lim} is the braking torque limit that the electrified powertrain can provide.

Meanwhile, based on the feedback signal of the real value of the regenerative braking torque, the target values of the front-wheel cylinder pressure (p_{f_tgt}) and the rear-wheel cylinder pressure (p_{r_tgt}) can be figured out respectively, as equation (11) and equation (12) express [2].

$$p_{f\_tgt} = \frac{T_{b\_f} - T_{reg\_real}}{4\pi\mu_b r_f^2 R_{e\_f}} \tag{11}$$

$$p_{r\_tgt} = \frac{T_{b\_r}}{4\pi\mu_b r_r^2 R_{e\_r}} \tag{12}$$

where, r_r is the radius of the piston of the rear wheel cylinder, R_{e_r} is the effective friction radius of the rear brake disc.

Thus, the by-wire brake system can modulate the front and rear wheel cylinder pressures to the target values separately based on the above calculation results. And finally, the regenerative braking torque provided by the electrified powertrain and the friction braking force generated by the by-wire brake will meet the total brake request of the vehicle.

System Modeling

In order to verify the feasibility and effectiveness of the proposed regenerative braking control algorithm, simulation is required. Before the simulation, appropriate models including the vehicle, the electric powertrain and the by-wire brake system need to be built.

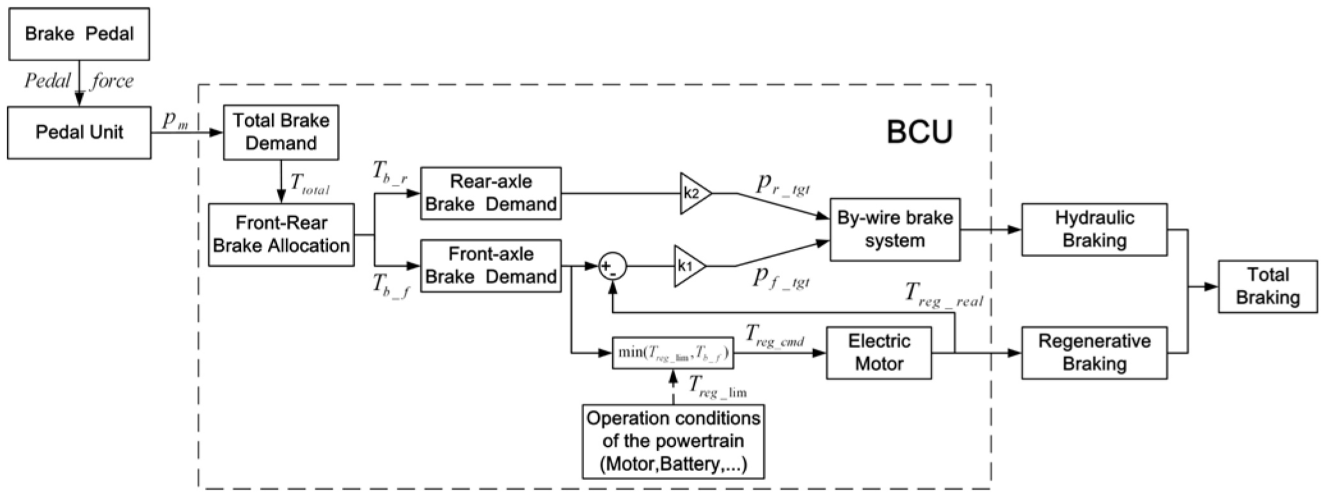

Figure 5. Cooperative regenerative braking algorithm based on the by-wire brake system.

Vehicle Dynamics

A comprehensive model of vehicle dynamics with eight degrees of freedom has been built in MATLAB/Simulink and validated by the present authors [2]. Since the lateral dynamic control of the vehicle is not involved in the present article, only the longitudinal motion of the vehicle is modeled. The longitudinal dynamics of the vehicle during deceleration processes can be modeled according to the equation [17]:

$$m \cdot \frac{du}{dt} = -F_b - f \cdot mg - \frac{1}{2} C_D A \rho \cdot u^2 - mg \cdot \sin\alpha \tag{13}$$

where, m is the overall mass of the vehicle, u is the longitudinal velocity, F_b is the total braking force, f is the coefficient of rolling resistance, C_D is the coefficient of air resistance, A is the frontal area of the vehicle, ρ is the density of air, and α is the angle between the road and the horizontal.

The key parameters of the target electric car are shown in Table 1.

Table 1. Parameters of the target electric vehicle.

Parameter	Value
Total mass (m/kg)	1250
Wheel base (L/m)	2.50
Frontal area (A/m²)	2.40
Nominal radius of tyre (r/m)	0.295
Final drive ratio (i_0)	3.79
Transmission ratio (i_g)	2.10

Electric Motor

The model of the electric motor is built according to the test data from an electric motor applied in a commercialized electric vehicle [2]. The peak torque of the electric drive system is 145 *N·m* and its nominal power is 29 *kW*. The efficiency map of the motor in the regenerative braking mode has almost the same symmetry as that in the driving mode with respect to the axis of rotational speed. The torque of the electric motor is considered as a first-order reaction, which can be expressed as:

$$\tau \cdot \dot{T}_{reg,real} + T_{reg,real} = T_{reg,cmd} \tag{14}$$

where, $T_{reg,real}$ is the real value of the motor torque detected by MCU, $T_{reg,\ cmd}$ is the command value of the motor torque.

By-Wire Brake System

In the by-wire brake system, the hydraulic braking pressure in downstream of the brake circuit is offered by the high-pressure supply unit, which is comprised of a high pressure accumulator and a hydraulic pump-motor. Since the pressure in the high pressure accumulator p_{hsu} always keeps at a considerable high level, the high-pressure supply unit in the upstream can be modeled as:

$$p_{hsu} = p_0 \quad (p_0 = Const.) \tag{15}$$

The wheel cylinder pressure in the downstream of the hydraulic brake circuit is modulated by the inlet valve and the outlet valve. The structure of the wheel cylinder is simplified to a piston and a spring. The wheel cylinder pressure can be expressed as [19]:

$$\frac{dp_w}{dt} = \frac{k}{\pi^2 r_w^4} C_d A_c \sqrt{\frac{2\Delta p}{\rho_h}} \tag{16}$$

where, k is the spring stiffness of the wheel cylinder, r_w is the radius of the piston of the wheel cylinder, C_d is the flow coefficient of the valve, A_c is the cross-sectional area of the valve opening and ρ_h is the density of the hydraulic fluid.

Hardware-in-the-Loop Simulation

To validate and evaluate the control strategy and algorithm of the cooperative regenerative braking, hard-ware-in-the-loop (HIL) simulations are carried out.

HIL Simulation Platform

Figure 6 illustrates the configuration of the hardware-in-the-loop simulation system for the regenerative braking control system. The entire system is comprised of a real-time simulation system and a real brake control unit. The real-time simulation system is the AutoBox from dSPACE. Virtual models, including vehicle dynamics, the battery, the tyre, and the electric motor are embedded in the AutoBox. The brake control unit is a real controller, which is identical to the one installed on a vehicle.

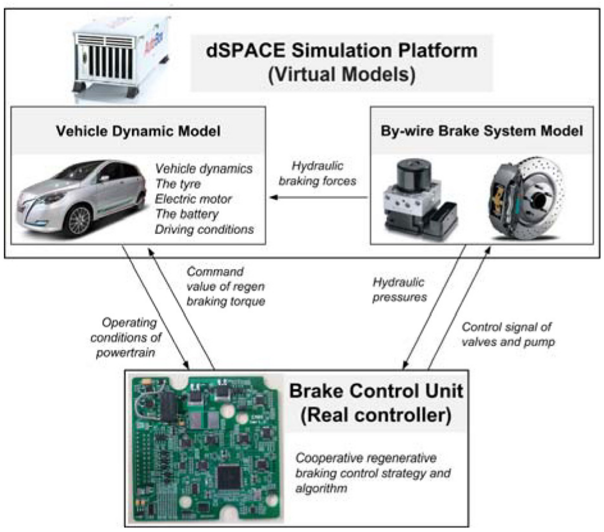

Figure 6. Cooperative regenerative braking algorithm.

Simulation Scenario Set-Up

The simulations are carried out during scenarios of the normal deceleration processes. In simulation, the initial braking speed is set at 30km/h, and the braking pressure at master cylinder is taken as a ramp input stabilizing at 3MPa, and the road is assumed to have a dry surface with a high adhesion coefficient.

Taking the original BFD allocation as a baseline strategy, the regeneration efficiencies of the baseline strategy and the newly proposed regenerative braking control algorithm are compared during the normal braking processes.

Simulation Results and Analysis

The simulation results of the two different regenerative braking control strategies, namely the baseline strategy and the proposed strategy, are shown in Figure 7 and Figure 8 respectively.

For an electric car with the original regenerative braking control strategy, as shown in Figure 7, since the front-rear braking force distribution is set as a fixed value, the rear-wheel braking pressure keeps the same value with the master cylinder pressure without any modulation during the whole braking process.

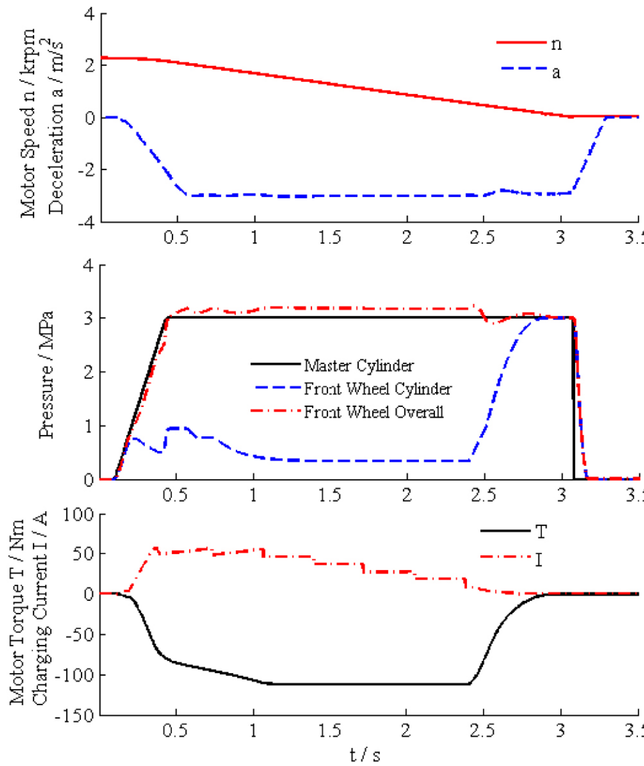

Figure 7. Simulation results of the baseline regenerative braking control strategy.

Under the proposed regenerative braking control strategy, the simulation results are shown in Figure 8. At the beginning of the deceleration procedure, the regenerative braking torque of the electric motor is exerted gradually on the front axle, and the front-wheel brake pressure is regulated by the by-wire brake system based on the proposed braking force allocation, while the rear-wheel brake is not applied. After 0.35s, the master cylinder pressure reaches 3MPa, leading to the brake demand of the vehicle increasing accordingly. The regenerative brake and the mechanical brake couple in the front axle. In the meantime, the rear-wheel brake force starts to be applied and dynamically modulated by the by-wire brake modulator, and its pressure is much lower than the master cylinder pressure, which is due to the defined control strategy. At about 2.4s, the vehicle speed decreases to a relatively low value. Limited by its full-load characteristics, regenerative braking torque drops significantly. Thus, the front hydraulic pressure increases correspondingly to supplement the vehicle's brake request.

And the front and rear hydraulic pressures are still modulated by the by-wire brake modulator based on the proposed distribution strategy. During the whole deceleration, the regenerative brake and the frictional brake cooperate well and the braking deceleration changes smoothly, guaranteeing the braking performance of the vehicle.

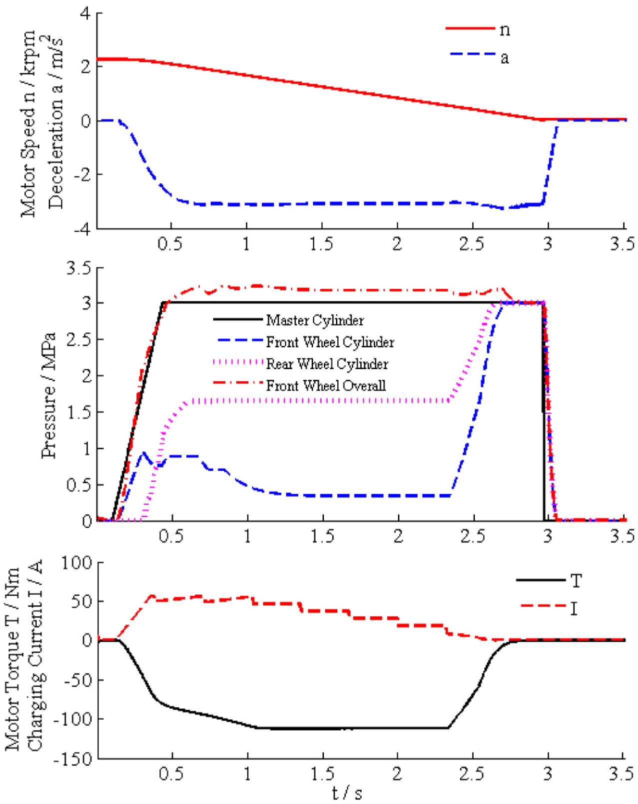

Figure 8. Simulation results of the proposed regenerative braking control algorithm.

To evaluate the energy regeneration performance by the proposed control algorithm during regenerative brake, the regeneration efficiency η_{reg} is adopted as an evaluation parameter, which can be expressed as [20]:

$$\eta_{reg} = \frac{E_{reg}}{E_{recoverable}} \times 100\% \tag{17}$$

where E_{reg} is the energy regenerated by the regenerative braking system, $E_{recoverable}$ is the maximum value of the recoverable energy, i.e. the kinetic energy left after subtracting all the energy that would be dissipated by road drag and air resistance.

The regenerated energy is expressed by [2]:

$$E_{reg} = \int_{t0}^{t1} UIdt \tag{18}$$

The recoverable energy by

$$E_{recoverable} = \frac{1}{2}mv^2 - \int_0^{t1} fmgvdt - \int_0^{t1} \frac{C_D \cdot A}{21.15} \cdot (3.6v)^2 \cdot vdt \tag{19}$$

where t_0 is the initial braking time, and t_1 is the final braking time. *U* is the output voltage of battery pack. *I* is the charging current of battery.

Table 2. HIL simulation results of the regenerative brake under the two different control algorithms

Control strategy	Recoverable energy [kWh]	Regenerated energy [kWh]	Regeneration efficiency [%]	Efficiency improvement [%]
Baseline	39.84	25.87	64.94	-
Proposed	39.98	32.02	80.10	23.36

The regeneration results under normal braking process are shown in Table 2. According to data, the regeneration efficiency of the original control strategy is 64.94%, while the regeneration efficiency of the proposed control algorithm is 80.10%. The improvement of the regeneration efficiency by the proposed control algorithm based on by-wire brake system is above 23%.

Conclusions

In order to further explore the potential of the braking energy regeneration of electrified vehicles, a regenerative braking control algorithm based on a by-wire brake system was proposed.

The layout of the adopted brake-by-wire system was introduced. The proposed regenerative braking control algorithm based on brake-by-wire system was illustrated. The models of the main components related to the regenerative brake and the frictional brake of the target electric passenger car were built in MATLAB/Simulink. The control effects and regeneration efficiencies of the proposed control strategy are hard-ware-in-the-loop simulated and compared with the original strategy.

The HIL simulation results show that the proposed regenerative braking control algorithm is advantageous with respect to the regeneration efficiency. The regeneration efficiency of the original control strategy is 64.94%, while the regeneration efficiency of the proposed control algorithm reaches 80.10%. The improvement of the regeneration efficiency by the proposed control algorithm based on by-wire brake system is above 23%.

References

1. Gao, Y., Chen, L., and Ehsani, M., "Investigation of the Effectiveness of Regenerative Braking for EV and HEV," SAE Technical Paper 1999-01-2910, 1999, doi:10.4271/1999-01-2910.
2. Zhang, J.Z., Lv, C., Gou, J.F. and Kong, D.C., "Cooperative control of regenerative braking and hydraulic braking of an electrified passenger car", Proceedings of the Institution of Mechanical Engineers, Part D: Journal of Automobile Engineering 2012; 226(10): 1289-1302.
3. Zhang, J.Z., Chen, X., Zhang, P.J., "Integrated control of braking energy regeneration and pneumatic anti-lock braking", Proceedings of the Institution of Mechanical Engineers, Part D: Journal of Automobile Engineering 2011; 224(5): 587-610.

4. Gao, Y. and Ehsani, M., "Electronic Braking System of EV And HEV---Integration of Regenerative Braking, Automatic Braking Force Control and ABS," SAE Technical Paper 2001-01-2478, 2001, doi:10.4271/2001-01-2478.
5. Zhang, J.Z., Kong, D.C., Lv, C., Chen, X., "Optimization of control strategy for regenerative braking of electrified bus equipped with ABS", Proceedings of the Institution of Mechanical Engineers, Part D: Journal of Automobile Engineering 2012; 226(4): 494-506.
6. Jonner, W., Winner, H., Dreilich, L., and Schunck, E., "Electrohydraulic Brake System - The First Approach to Brake-By-Wire Technology," SAE Technical Paper 960991, 1996, doi:10.4271/960991.
7. Sundar, M. and Plunkett, D., "Brake-by-Wire, Motivation and Engineering - GM Sequel," SAE Technical Paper 2006-01-3194, 2006, doi:10.4271/2006-01-3194.
8. Roberts, M. and Chhaya, T., "An Approach to the Safety Design and Development of a Brake-by-Wire Control System," SAE Technical Paper 2011-01-0212, 2011, doi:10.4271/2011-01-0212.
9. Nakamura, E., Soga, M., Sakai, A., Otomo, A. et al., "Development of Electronically Controlled Brake System for Hybrid Vehicle," SAE Technical Paper 2002-01-0300, 2002, doi:10.4271/2002-01-0300.
10. Ohtani, Y., Innami, T., Obata, T., Yamaguchi, T. et al., "Development of an Electrically-Driven Intelligent Brake Unit," SAE Technical Paper 2011-01-0572, 2011, doi:10.4271/2011-01-0572.
11. Yeo, H., Koo, C., Jung, W., Kim, D. et al., "Development of Smart Booster Brake Systems for Regenerative Brake Cooperative Control," SAE Technical Paper 2011-01-2356, 2011, doi:10.4271/2011-01-2356.
12. von Albrichsfeld, C. and Karner, J., "Brake System for Hybrid and Electric Vehicles," SAE Technical Paper 2009-01-1217, 2009, doi:10.4271/2009-01-1217.
13. Aoki, Y., Suzuki, K., Nakano, H., Akamine, K. et al., "Development of Hydraulic Servo Brake System for Cooperative Control with Regenerative Brake," SAE Technical Paper 2007-01-0868, 2007, doi:10.4271/2007-01-0868.
14. Ko, J., Lee, G., Ko, S., Ahn, S. et al., "Co-operative Control of Regenerative Braking using a Front Electronic Wedge Brake and a Rear Electronic Mechanical Brake Considering the Road Friction Characteristic," SAE Technical Paper 2012-01-1798, 2012, doi:10.4271/2012-01-1798.
15. Zhou, Z., Mi, C., Zhang, G., "Integrated control of electromechanical braking and regenerative braking in plug-in hybrid electric vehicles," International Journal of Vehicle Design 2012; 58(2): 223-239.
16. Gao, Y. and Ehsani, M., "Electronic Braking System of EV And HEV---Integration of Regenerative Braking, Automatic Braking Force Control and ABS," SAE Technical Paper 2001-01-2478, 2001, doi:10.4271/2001-01-2478.
17. Pacejka H., "Tyre and vehicle dynamics," Elsevier, 2005.
18. Zhang, J., Lv, C., Yue, X., Qiu, M. et al., "Development of the Electrically-Controlled Regenerative Braking System for Electrified Passenger Vehicle," SAE Technical Paper 2013-01-1463, 2013, doi:10.4271/2013-01-1463.
19. Zhang, J., Lv, C., Yue, X., Li, Y., Yuan, Y., "Study on a linear relationship between limited pressure difference and coil current of on/off valve and its influential factors", ISA Transactions 2014; 53(1): 150-161.
20. Zhang, J., Lv, C., Qiu, M., Li, Y., Sun, D., "Braking energy regeneration control of a fuel cell hybrid electric bus", Energy Conversion and Management 2013; 76: 1117-1124.

Acknowledgments

The authors would like to thank the Natural Science Foundation of China [Project no. 51075225] and National High Tech Project "863" [Project no. 2011AA11A243] for funding this work.

The Engineering Meetings Board has approved this paper for publication. It has successfully completed SAE's peer review process under the supervision of the session organizer. The process requires a minimum of three (3) reviews by industry experts.

ISSN 0148-7191

http://papers.sae.org/2014-01-1791