

Development of Electric Servo Brake System

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ABSTRACT

An electric servo brake system realizing good brake feel while making effective use of regenerative braking has been developed in order to increase power efficiency in electric vehicles and fuel efficiency in hybrid electric vehicles. This system controls brake pressure using hydraulic pressure cylinders with an electric motor as the drive source. By means of this configuration, it realizes high-accuracy brake pressure control that cooperates with regenerative braking, and its use in the Fit EV has increased power regeneration by 8% against a conventional system based on EPA fuel economy standards. In addition, the use of a configuration in which the pedal operation section is independent from the brake pressure generation section helps to prevent the pedal force from being affected by brake pressure control, making it possible to realize good brake feel.

1. Introduction

Against the background of increasing demands for the reduction of fuel consumption and CO₂ emissions in order to protect the global environment, electric vehicles (EV), hybrid electric vehicles (HEV), and other vehicles fitted with electric power trains are attracting increased attention year by year. EV and HEV are able to realize increased power and fuel efficiency by recovering kinetic energy as regenerated energy through the use of regenerative brakes when decelerating. It is therefore important to efficiently produce regenerative braking energy during deceleration in order to increase the amount of regenerated power. What is needed in order to realize this goal is brake systems provided with a cooperative regenerative braking function, making it possible, in response to the state of the system, to cooperatively allocate friction and regenerative braking force for the braking force demanded by the driver. In order to realize the braking feel intended by the driver while producing regenerative braking force, it is necessary to constantly coordinate the total of regenerative braking force and friction braking force with the value demanded by the driver^{(1), (2)}. To realize the same good brake feel as a normal brake system using a vacuum booster at this time, it is desirable that the pedal force should not be affected by brake pressure control.

A variety of systems have been proposed to date in order to realize a cooperative regenerative braking function at the same time as achieving a good brake feel. These include brake-by-wire systems⁽³⁾, in which the brake pressure is controlled independently for each wheel, and systems that employ identical pressure for each wheel while being capable of freely generating brake pressure as demanded;

these latter systems include hydraulic booster types^{(4), (5)}, vacuum booster types⁽⁶⁾, and electric booster types⁽⁷⁾. The realization of a good brake feel during cooperative regenerative braking has represented an issue for systems in which the pedal operation section and the brake pressure generation section are linked, because pedal force can be affected by brake pressure control. An electric servo brake system has therefore been newly developed in order to contribute to increased power efficiency in EV and fuel efficiency in HEV by realizing a cooperative regenerative braking function while addressing this issue. The developed system employs a configuration in which the pedal operation section and the brake pressure generation section are independent. It employs a pedal stroke and pedal force simulation function in the pedal operation section. The brake pressure generation section generates friction braking force by means of brake pressure control using hydraulic cylinders, with an electric motor as the drive source, and is able to freely control brake pressure.

This paper provides an overview of the developed electric brake system, and discusses element technologies related to brake pressure control and the cooperative regenerative braking function.

2. Development Goals

In order to reconcile the reduction of power consumption in EV and fuel consumption in HEV with brake performance, the following main aims were set for the development of the electric servo brake system:

- (1) Realization of a cooperative regenerative braking function and the achievement of a high level of regeneration efficiency

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- (2) Realization of good brake feel
- (3) Realization of better non-servo performance than a conventional brake system

3. System Overview

The developed system is composed of a pedal feel simulator, a tandem motor cylinder, a brake pedal, a pedal stroke sensor, and an ECU, as shown in Fig. 1. The pedal feel simulator produces a pedal stroke and pedal force when the brake pedal is operated. The tandem motor cylinder generates brake pressure as commanded by the ECU based on the degree of pedal operation detected by the pedal stroke sensor.

3.1. Pedal Feel Simulator

As Fig. 2 shows, the pedal feel simulator is made up of a master cylinder, a stroke simulator, a solenoid valve, and a hydraulic pressure sensor.

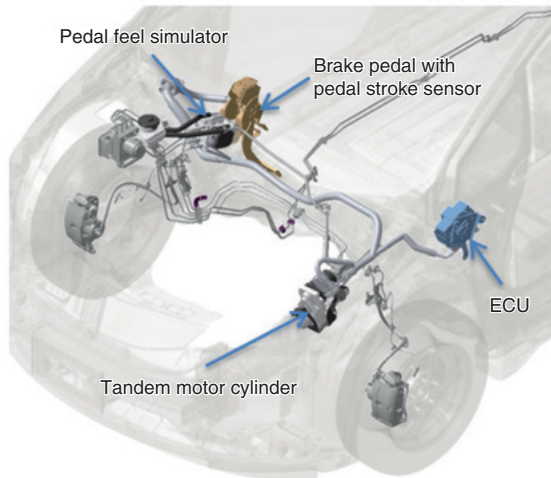


Fig. 1 Overview of electric servo brake system

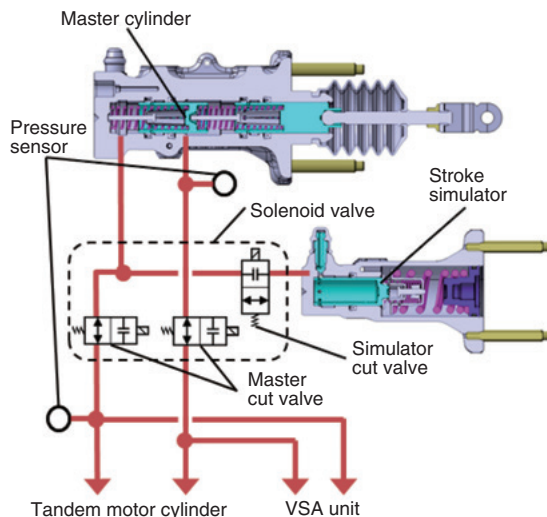


Fig. 2 Structure of pedal feel simulator

The master cylinder is linked to the brake pedal, and connected to the stroke simulator by a hydraulic channel. A simulator cut valve and a hydraulic pressure sensor are positioned in this hydraulic channel. The simulator cut valve is a normally closed solenoid valve. The pedal stroke and pedal force simulation functions are realized by means of this configuration. The pedal force characteristic can be adjusted by setting the brake pedal link ratio and the spring reaction force characteristic of the stroke simulator.

The master cylinder and the tandem motor cylinder are also connected by a hydraulic channel, and a master cut valve and hydraulic pressure sensor are positioned in this hydraulic channel. The master cut valve is a normally open solenoid valve. In addition, the tandem motor cylinder and the Vehicle Stability Assist (VSA) unit are connected by a hydraulic channel downstream from the master cut valve. Because the brake pressure generated by the tandem motor cylinder is isolated in this configuration, pedal force is not affected by brake pressure control. In addition, the hydraulic circuits are switched at system start-up and shutdown.

3.2. Tandem Motor Cylinder

As shown in Fig. 3, the tandem motor cylinder is made up of a brushless motor, a reduction gear, a ball screw and a slave cylinder. A resolver is built into the brushless motor.

The brushless motor and the slave cylinder are connected by the reduction gears and the ball screw. Brake pressure is generated by direct pressure of the ball screw on the slave cylinder piston, making possible high-accuracy brake pressure control.

Figure 4 shows the operation of the electric servo brake system when it is generating brake pressure. Based on the degree of pedal operation detected by the pedal stroke sensor, the ECU decides on a brake pressure target, and the brake pressure control, which will be discussed below, generates the brake pressure by simultaneously operating the brushless motor and closing the master cut valve. The brake pressure is transmitted to the wheel cylinder via the VSA unit.

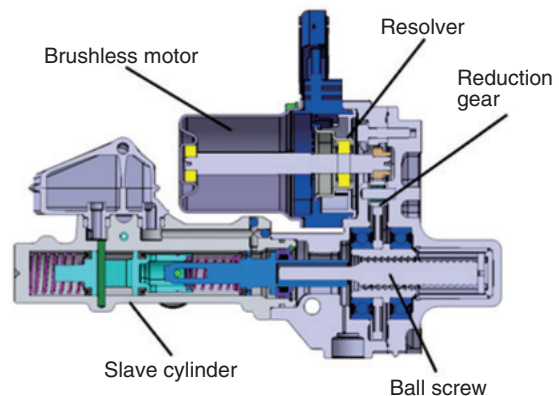


Fig. 3 Structure of tandem motor cylinder

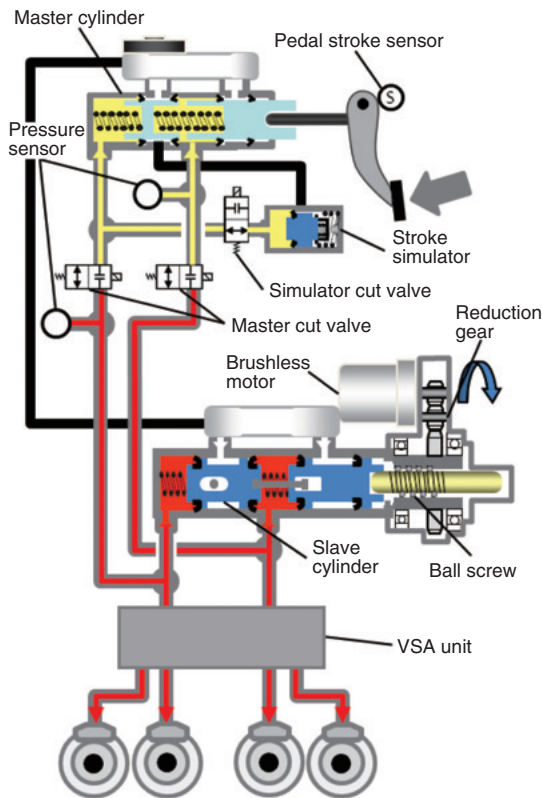


Fig. 4 System configuration diagram

4. Brake Characteristics

4.1. Basic Brake Characteristics

In order to realize good brake feel, the brake pedal link ratio and the spring reaction force characteristic of the stroke simulator were adjusted in order to achieve a pedal force characteristic similar to that of a standard brake system. Figure 5 shows a comparison of the pedal force characteristic of the electric servo brake system and a standard brake system. Appropriate adjustment of the parameters discussed above has made it possible to realize a similar pedal force characteristic in the electric servo brake system as displayed by a standard brake system.

The setting for the brake pressure target in relation to the degree of pedal operation was also adjusted with the aim of achieving a similar characteristic in terms of the effectiveness of braking to a standard brake system. Figure 6 shows a comparison of the brake effectiveness characteristic of the electric servo brake system and a standard brake system. The electric servo brake system realizes a similar brake effectiveness characteristic to the standard brake system. Together, this brake effectiveness characteristic and the pedal force characteristic produce a good brake feel.

4.2. Non-servo Performance

The system employs a configuration in which the pedal input is transmitted directly to the master cylinder and brake

pressure is generated and transmitted to the wheel cylinder when the servo is not in use, for example when the system is shut down. Adjustment of the brake pedal link ratio and the cross-sectional area of the master cylinder piston has doubled the hydraulic pressure generated at a pedal force of 500 N when the servo is not in use against a vacuum booster brake system.

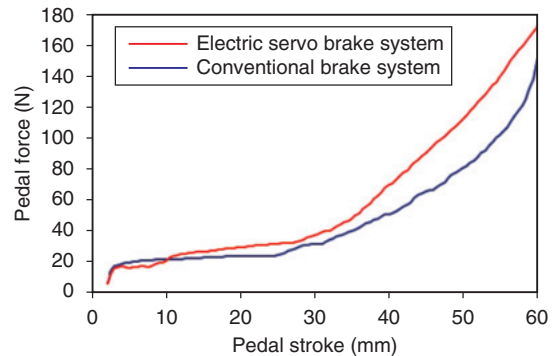


Fig. 5 Pedal force characteristic

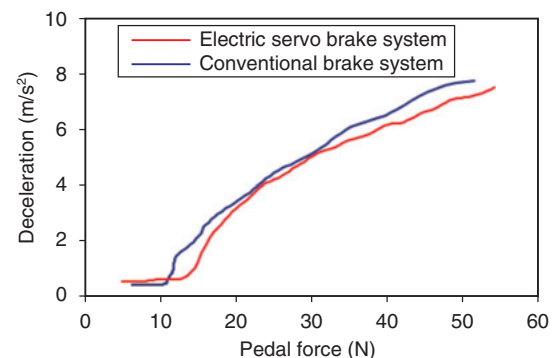


Fig. 6 Braking effectiveness

5. Brake Pressure Control

Brake pressure control functions as follows. First, a brake pressure target is decided on the basis of the degree of pedal operation and data concerning the upper limit value of regenerative torque able to be produced by the power train. Next, the brushless motor is operated by means of the hydraulic pressure control section and the motor angle control section shown in Fig. 7, and the target brake pressure is generated.

The hydraulic pressure control section outputs a stroke target for the slave cylinder piston in response to the brake pressure target. The hydraulic pressure control section is made up of a feedforward section and a feedback section. The feedforward section uses the slave cylinder piston stroke and a characteristic map of the generated brake pressure. Values from the hydraulic pressure sensor positioned downstream from the master cut valve are input to the feedback section. Figure 8 shows the brake pressure response. As Fig. 8 shows, this hydraulic pressure control

configuration has made it possible to realize good response to, and good tracking performance of, brake pressure. Figure 9 shows the slave cylinder pressure response during ABS operation. Even in a situation in which the brake load fluctuates, such as ABS operation, the system displays adequate control stability and realizes high-accuracy hydraulic pressure control.

The motor angle control section employs angle feedback control using a resolver, and outputs a motor drive voltage. In addition, in order to realize a high level of responsiveness from the compact brushless motor, Flux Weakening Control (FWC) has been employed to make it possible to increase the motor's speed⁽⁸⁾. Figure 10 shows a comparison of the step response of brake pressure and motor speed with and without flux weakening control. The use of flux weakening control increases motor speed by 30% and reduces response time by 25%, making it possible to realize a high level of responsiveness from a compact motor.

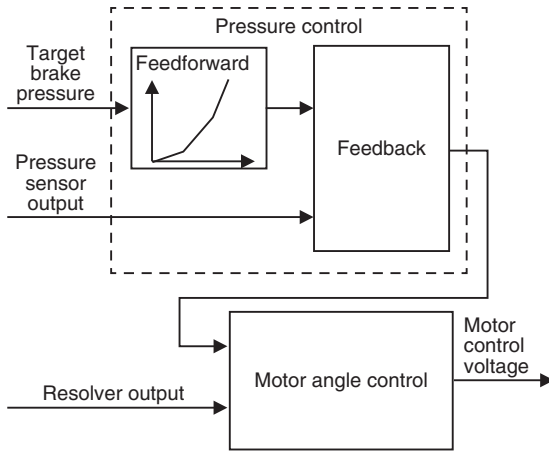


Fig. 7 Block diagram of brake pressure control

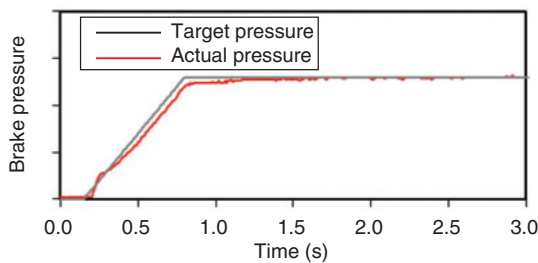


Fig. 8 Response of brake pressure

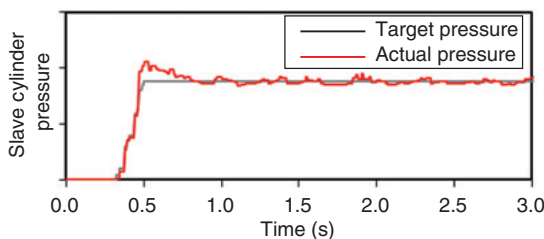
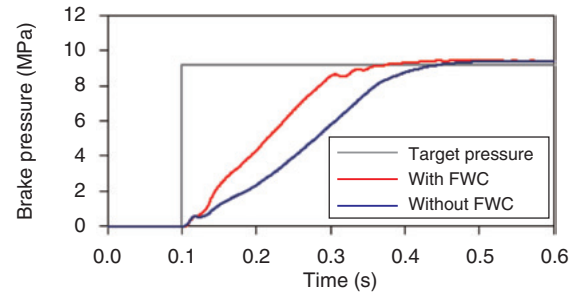
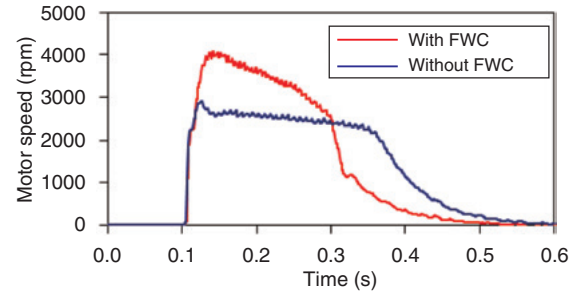


Fig. 9 Slave cylinder pressure response during ABS operation



(a) Brake pressure



(b) Motor speed

Fig. 10 Step response with flux weakening control (FWC)

6. Cooperative Regenerative Braking

The reduction of energy loss when friction brakes are employed during vehicle operation is an important factor in increasing the power and fuel efficiency of EV and HEV. One of the demands on cooperative regenerative braking is therefore to make as little use of the friction brakes as possible. However, there are situations in which regenerative brakes are not able to generate power due to the status of the power train, for example when the vehicle is traveling at high speeds and immediately before the vehicle stops. Unless it is possible to rapidly switch to the friction brakes in these cases, fluctuations in the degree of deceleration contrary to the driver's expectations will occur. Because of this, a high-accuracy brake pressure control system is essential to the realization of increased fuel efficiency by means of cooperative regenerative braking. The use of a configuration in which the pedal operation section and the brake pressure generation section are independent, in addition to the high-accuracy brake pressure control discussed above, have helped to enable high regeneration efficiency to be reconciled with the realization of good brake feel in the electric servo brake system.

Figure 11 shows time history data for cooperative regenerative braking control in the electric servo braking system during regular braking from 70 km/h. Until immediately before the vehicle stops, the frictional brakes are not used at all, and the vehicle's kinetic energy is recovered using the regenerative brakes alone. The degree of deceleration is constant and consistent with the driver's expectation, and there is no change in the brake feel due

to regeneration. Because the regenerative brakes cannot be used immediately before the vehicle stops and while it is stopped, it is necessary to switch to the friction brakes. The characteristics of the electric servo brake system's high-accuracy hydraulic brake pressure control have made it possible to reduce vehicle speed at the completion of the switching, V_e , to 2 km/h. In the FIT EV, the use of the electric servo brake system has increased regeneration amount by 8% against a conventional system as measured by EPA fuel efficiency rating standards.

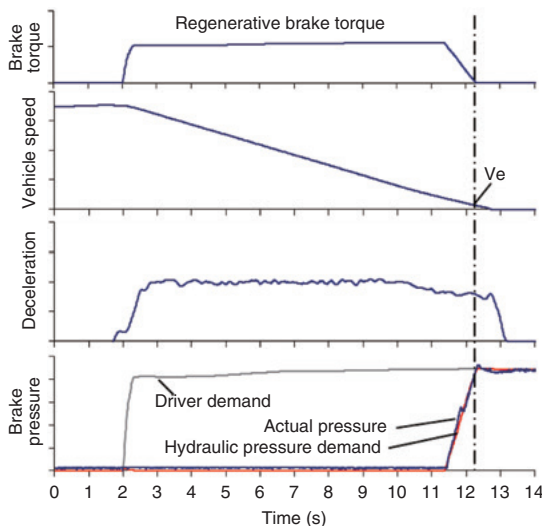


Fig. 11 Time chart of regeneration braking

7. Conclusion

An electric brake system realizing good controllability has been developed. The system generates brake pressure using a configuration that separates the pedal operation and brake pressure generation sections and employs an electric motor, a ball screw, and hydraulic cylinders. The system both realizes increased energy recovery efficiency during the use of cooperative regenerative braking and offers the driver smooth, natural braking feel. It is hoped that the development of this electric servo brake system will contribute significantly to the further spread of electric vehicles.

Details of the main technologies employed in the system can be summarized as follows.

- (1) The use of motor angle control, in addition to hydraulic pressure control comprising feed forward and feedback control and flux weakening control, has made it possible to realize high-accuracy and highly responsive electric brake control, thus realizing high regeneration efficiency.
- (2) The use of a configuration in which the pedal operation section is independent of the brake pressure generation section, optimization of the simulator spring reaction force characteristic and the brake pedal link ratio, and the use of high-accuracy and highly responsive electric brake control has made it possible to realize a brake feel equivalent to that offered by a standard brake system.

- (3) Optimization of the brake pedal link ratio and the cross-sectional area of the master cylinder pistons has made it possible to realize a higher level of non-servo performance than a conventional vacuum booster brake system.

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