

Development of New Electronically Controlled Hydraulic Unit for Various Applications

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ABSTRACT

The use of hybrid, fuel cell electric, and pure electric vehicles is on the increase as part of measures to help reduce exhaust gas emissions and to help resolve energy issues. These vehicles use regenerative-friction brake coordination technology, which requires a braking system that can accurately control the hydraulic brakes in response to small changes in regenerative braking. At the same time, the spread of collision avoidance support technology is progressing at a rapid pace along with a growing awareness of vehicle safety. This technology requires braking systems that can apply a large braking force in a short time. Although brake systems that have both accurate hydraulic control and large braking force have been developed in the past, simplification is required to promote further adoption. This paper describes the following three items: (1) an examination of the brake system functions that realize the regenerative-friction brake coordination and collision avoidance support functions, (2) considerations and a proposal for a brake system that achieves the functions described in item (1) with a simple structure, and (3) development of core technology for controlling the wheel cylinder pressure in a brake system equipped with a hydraulic regulator.

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INTRODUCTION

From the second half of the 1990s, the use of hybrid, fuel cell electric, and pure electric vehicles has been on the increase as part of measures to help reduce exhaust gas emissions and resolve energy issues. In these vehicles, regenerative-friction brake coordination technology, which controls the vehicle braking force while converting kinetic energy during deceleration to electrical energy, plays an important role in enhancing fuel efficiency.

At the same time, the spread of advanced safety technologies such as autonomous emergency braking systems, which aim to alleviate the effects of a collision, is progressing at a rapid pace. Sensing technologies that detect the conditions around the vehicle instead of the driver, have been attracting particular attention as part of this trend. However, the steering and braking devices that control vehicle behavior after the detection of the conditions around the vehicle are still extremely important.

The further development of these technologies is regarded as an essential part of maintaining the automobile as a principle means of transportation in the future.

This paper reviews the requirements of such a brake system and proposes a new simplified electronically controlled hydraulic unit and a control method of the pressure application unit. The proposed system uses an easily adoptable structure for regenerative-friction brake coordination and autonomous emergency braking in addition to commonly used traction and vehicle stability control (TRC/VSC) applications.

REQUIREMENTS OF ELECTRONICALLY CONTROLLED HYDRAULIC UNIT FOR VARIOUS APPLICATIONS

This section describes the requirements of the electronically controlled hydraulic unit for various applications introduced in the previous section. [Table 1](#) lists the requirements for each application. The details are described following the table.

Table 1. Outline of braking force control performance of electronically controlled hydraulic unit required by each application.

		Required performance		
		Size of braking force	Rate of braking force change	Accuracy of braking force
Type of application	Regenerative-friction brake coordination	Small	Low	High
	Service brake	Small to high (the residual performance if a system fault occurs must be equivalent to a conventional system)	Low to extremely high	High
	Autonomous emergency braking system	Large	High to extremely high (according to the sensor type and compatible vehicle speed range of system)	Normal
	Traction control	Small	Medium	Normal
	Vehicle stability control	Large	High	Normal

Requirements to Achieve Regenerative-Friction Brake Coordination Functions

Generally, the maximum deceleration realized by regenerative brakes is between 1 and 3 m/s². Furthermore, a larger fuel efficiency improvement can be achieved if this figure can be increased. However, increasing maximum deceleration also increases the weight of the system and vehicle. A larger regenerative brake generator, inverter, and battery are needed. Due to the trade-off effect on fuel efficiency by increasing the weight of the vehicle, it is likely that there will be no major changes in maximum regenerative brake deceleration in the future. Therefore, the size of the required vehicle braking force is likely to remain in accordance with this value.

Regenerative brakes have three distinguishing features.

1. Regenerative brakes operate with high accuracy and fast response [1].
2. Unlike hydraulic brakes, which exert braking force to stop the vehicle, regenerative brakes exert braking force in both the direction of vehicle travel and the opposite direction. Consequently, if regenerative brakes are used continuously, the vehicle may start to travel in the opposite direction. Therefore, the action of regenerative brakes must be halted before the vehicle reaches a stop.
3. Depending on the state of various systems (such as the battery charging state), it may not be possible to achieve the desired braking force using regenerative brakes. However, it is possible to identify whether the regenerative brakes can achieve the desired braking force in advance.

An electronically controlled hydraulic unit must be capable of securing the required vehicle braking force while ensuring compatibility with these regenerative brake features. Specifically, it is important to achieve highly accurate application of relatively small braking forces. However, from the standpoint of the speed of response, extreme high performance is not a requirement since the operation of the regenerative brakes is identified and limited in advance.

In addition, if the function of the service brake is performed by the electronically controlled hydraulic unit during regenerative-friction brake coordination, the following additional points are also required.

4. A large braking force must be exerted to achieve the required vehicle deceleration.
5. Braking force must be changed rapidly in accordance with various driver brake pedal operations.
6. The residual performance if an electronically controlled hydraulic unit fault occurs must be equivalent to that of a conventional system.

Requirements to Achieve Autonomous Emergency Braking System Functions

Autonomous emergency braking systems are control devices that use various sensors to detect vehicles, pedestrians, and objects around the vehicle and then generate braking force, regardless of driver operation. These systems may cause driver discomfort if braking force is generated too early. An electronically controlled hydraulic unit in an autonomous emergency braking system would be required to generate vehicle braking force equivalent to 10 m/s² in as short a time as possible. Since the timing of braking force generation that leads to driver discomfort is virtually unique to each driver, the applicable range of autonomous emergency braking systems can be enlarged by shortening the time in which the required vehicle braking force is achieved.

Requirements to Achieve TRC and VSC

TRC and VSC are applications that stabilize vehicle motion by applying braking force at each wheel individually in accordance with the vehicle behavior and road surface. Excluding certain systems [2], this is usually achieved by transmitting the master cylinder pressure generated by pressure application actuators to each wheel as appropriate by controlling solenoid valves provided at each wheel.

TRC is achieved by coordinated control with the engine and motors as power sources, mainly in accordance with the friction (μ) of the road surface when the vehicle starts moving. The required master cylinder pressure is relatively low and the rate of changes in master cylinder pressure is also normal.

In contrast, VSC functions to stabilize changes in the lateral behavior of the vehicle while driving by coordinated control with the power sources described above. In this case, the required master cylinder pressure is high and the rate of change is also high.

PROPOSAL FOR ELECTRONICALLY CONTROLLED HYDRAULIC UNIT FOR VARIOUS APPLICATIONS

The previous section described the requirements for an electronically controlled hydraulic unit compatible with various applications. This section describes a system configuration that satisfies these requirements.

In this paper, the portion of the electronically controlled hydraulic unit that controls braking force is called the “pressure application unit.” Generally, such pressure application units consist of a power supply unit and a pressure control unit. Table 2 shows the relationship between the type of pressure application unit used in the brake system and hydraulic control performance.

Table 2. Relationship between pressure application unit and hydraulic control performance.

			Hydraulic control performance (the second row indicates the required level)		
Pressure application unit			Pressure increase performance	Pressure control accuracy	Residual performance if power supply fault occurs
Power supply	Pressure control unit		High	Good	Desirable performance
1	Auxiliary power supply	Electric motor-driven cylinder	High	Good	×*1
2		Electric motor-driven pump used to increase pressure	Medium	Good	×*1
3	High-pressure fluid built up in accumulator	Linear solenoid valve	High to very high*2	Good	△*3
4		Regulator*4	Very high	Normal	○*5

Notes:

*1 If a backup power supply equivalent to the usual power supply is present, the electric motor that acts as the pressure control unit will continue to function even if a fault occurs in the usual power supply system, enabling pressure control by the electronically controlled hydraulic unit.

*2 Extremely high pressure increase performance can be achieved by adopting multiple linear solenoid valves [2]

*3 Providing a relatively small backup power supply allows linear solenoid valve drive, enabling pressure control by the electronically controlled hydraulic unit even if a fault occurs in the usual power supply system.

*4 Only practically adopted for systems that drive the regulator using the driver pedal effort [3]

*5 Since the regulator can be driven using the driver brake pedal effort, pressure control can be performed by the electronically controlled hydraulic unit even if a fault occurs in the usual power supply system.

The first example of a system consists of a pressure application unit using the auxiliary battery as the power supply and a electric motor-driven cylinder as the pressure control unit. Several example of this type of system have already been proposed [4] and practically adopted. The advantages of these systems include pressure increase performance, pressure control accuracy, and compliance with various

applications. However, one disadvantage is that the pressure application unit itself stops operating if a power supply system fault occurs. Therefore, if the pressure application unit is used for the service brake functions as well, countermeasures such as redundant power supply systems should be considered.

The second system example consists of a pressure application unit using the auxiliary battery as the power supply and a pressure control unit that combines a pump for increasing pressure and an electric motor. Several examples of this type of system have also been practically adopted [5]. These systems generally use VSC actuators commonly adopted in conventional vehicles. Automakers are accustomed to using these actuators, which makes these systems easy to apply. However, the pressure increase performance of this type of pressure application unit is comparatively poorer than other systems. For this reason, this pressure application device is rarely used when service brake functions are required.

The third system example consists of a pressure application unit using high-pressure fluid built up in the accumulator as the power supply and linear solenoid valves for the pressure control unit. Since this type has extremely good pressure increase performance, it is mainly adopted in strong hybrid vehicles to perform braking functions, including that of the service brake [2,3]. The pressure increase performance can be set freely by adjusting the specifications and number of linear solenoid valves used. In addition, a relatively small auxiliary power supply can drive the linear solenoid valves if a fault occurs in the usual power supply system, and the high-pressure fluid already built-up in the accumulator can be used to continue hydraulic control for a certain period.

The fourth system example also consists of a pressure application unit using high-pressure fluid built up in the accumulator as the power supply. However, this system uses a regulator as the pressure control unit. This regulator mechanically controls the flow-in, stop, and discharge of high-pressure fluid with response to driver brake pedal operation. This system has particularly high pressure increase performance and is mainly adopted in large vehicles[6]. In addition, although the pressure control accuracy is limited by the individual mechanical hysteresis of the regulator, performance is sufficiently accurate to respond to driver brake pedal operations. However, it has not yet been applied to applications requiring highly accurate pressure control, such as regenerative-friction brake coordination.

This paper proposes a pressure application unit that uses high-pressure fluid built-up in an accumulator as a power supply and a regulator driven by linear solenoid valves as the pressure control unit. The aim of this pressure application method is to achieve both excellent pressure increase performance and pressure control performance by enhancing the pressure control accuracy of the regulator with the excellent pressure control performance of linear solenoid valves.

In addition, this system can also continue hydraulic control for a certain period of time if a fault occurs in the usual power supply system, without requiring an auxiliary power supply.

Figure 1 shows an outline of the proposed pressure application unit.