

Development of Hydraulic Servo Brake System for Hybrid Vehicle

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ABSTRACT

A new brake system, able to make efficient use of regenerative brakes while maintaining excellent brake feel, has been developed to increase the fuel economy of hybrid vehicles. A hydraulic servo was used as a base to enable mechanical operation of the service brakes; solenoid valves and brake fluid pressure sensors were added to this base to make it possible to control brake line pressure as demanded. The use of a stroke simulator in the hydraulic servo prevents brake feel from being affected by the control of the brake pressure.

In addition, high-accuracy brake pressure control that functions cooperatively with the regenerative brakes is enabled -- resulting in stable braking effectiveness. Fitted in a hybrid vehicle, this system has been shown to regenerate 46% more energy than the previous system.

1. Introduction

Hybrid vehicles are attracting increasing attention due to their ability to contribute to the protection of the global environment. In hybrid vehicle systems, the kinetic energy of the vehicle during deceleration is captured as regenerative energy and used to drive the motor, thereby reducing engine workload and increasing fuel economy. Making effective use of regenerative braking and increasing the regenerative energy are therefore important issues. However, if regenerative energy is simply increased, the regenerative brakes will apply more braking force than intended by the driver. In previous brake systems, regenerative brakes have not been used to the limit of their potential so that acceptable brake feel can be maintained. To make effective use of regenerative brakes while achieving brake feel matching the driver's expectations, it is

necessary to use cooperative control of the regenerative and hydraulic brakes to ensure that the total braking force matches the braking force demanded by the driver^{(1),(2)}.

Honda has developed a new brake system that realizes cooperative control of the regenerative and hydraulic brakes, and contributes to increased fuel economy in a hybrid vehicle. This system uses a hydraulic servo to operate the service brakes and a function that enables control of brake line pressure is added. Because the hydraulic servo is therefore important to the functioning of the service brakes, it was also necessary to redesign the service brakes to enhance performance and reliability.

This paper discusses the configuration of the newly developed brake system along with the element technologies used to enhance performance and reliability of the service brakes and realize cooperative control of the regenerative and hydraulic brakes.

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2. Development Concept

Brake-by-wire systems have recently come into use to enable a variety of brake control functions to be realized^{(3),(4)}. These systems allow brake line pressure to be controlled as demanded and also make it possible to realize cooperative control of regenerative and hydraulic brakes. However, because the service brakes are electronically controlled, it is necessary to ensure electrical reliability, and there are numerous concerns related to this area⁽⁵⁾⁻⁽⁷⁾.

The basic concept of the new system was to ensure reliability by using mechanical control of the service brakes. With this purpose, a mechanical hydraulic servo was used to operate the service brakes. And a configuration in which the output pressure of the hydraulic servo is controlled electronically by solenoid valves was selected, providing the ability to handle a variety of control functions.

3. Development Goals

The major elements of the new system are the service brakes and the brake line pressure control. The following development goals were established for each of these elements:

- (1) Service brakes
To realize excellent brake feel and ensure a high level of reliability.
- (2) Brake line pressure control
To develop a cooperative control system for regenerative and hydraulic brakes that would enable the regenerative brakes to be used efficiently while maintaining comfortable brake feel.

The development of a cooperative control system for the regenerative and hydraulic brakes required the following issues to be addressed.

The amount of torque that can be regenerated by a hybrid vehicle motor varies with vehicle speed and the state of charge of the battery. To use the regenerative energy to the limit of its potential while maintaining comfortable brake feel would require accurate control of the braking force to match dynamic changes in torque regeneration, as indicated in Fig. 1.

In standard brake systems, there is a fixed relationship between brake line pressure and pedal stroke. The pedal stroke therefore changes if control is applied to the brake line pressure, and brake feeling is affected. It is therefore necessary to maintain a fixed relationship between pedal force and stroke, even while cooperative control is applied to change the brake line pressure.

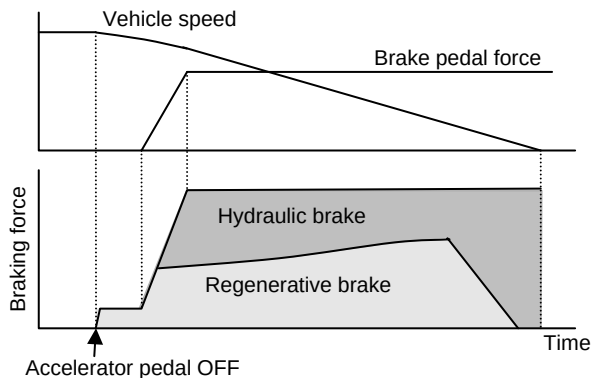


Fig. 1 Cooperative control of regenerative and hydraulic brakes

4. System Outline

The system is made up of the three components shown in Fig. 2.

- (1) Servo unit: Generates brake line pressure in response to brake pedal operation and controls brake line pressure as demanded.
- (2) Power unit: Functions as a power source for the servo unit. Generates high hydraulic pressures using an electronically controlled hydraulic pump; pressure is stored in an accumulator.
- (3) Pedal stroke sensor: Detects the stroke of the brake pedal.

4.1. Servo Unit

Figure 3 shows the configuration of the servo unit. A hydraulic servo section, consisting of a stroke simulator and a regulator valve positioned in a straight line, is connected to a master cylinder to enable mechanical control of the service brakes. Four solenoid valves and three pressure sensors are built into the hydraulic servo section, and an electronic control unit (ECU) is integrated. This enables brake line pressure to be controlled as demanded. The servo unit will be discussed in greater detail beginning in the next section.

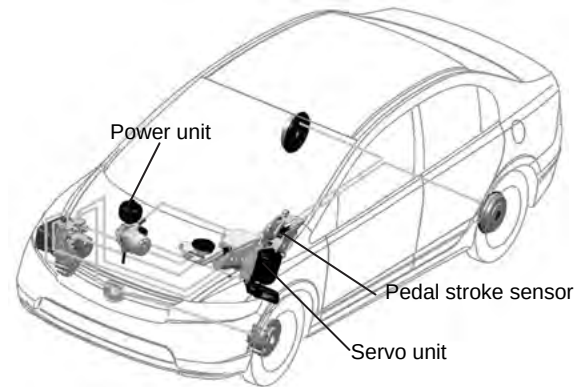


Fig. 2 System configuration

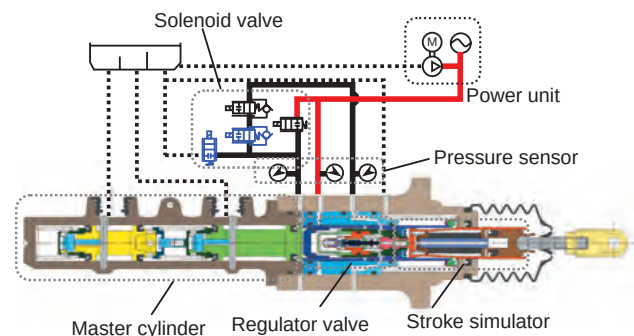


Fig. 3 Structure of servo unit

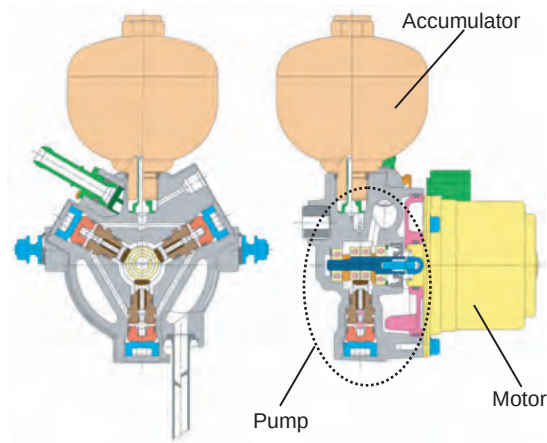


Fig. 4 Structure of power unit

4.2. Power Unit

As shown in Fig. 4, the power unit contains a 3-cylinder radial piston-type hydraulic pump driven by an electric motor. The pressure generated by the hydraulic pump is stored in an accumulator.

The power unit and the servo unit are connected by a pipe. The pressure in the accumulator is supplied to the servo unit; the regulator valves provide a sealing function. A pressure sensor is positioned in the pathways to monitor accumulator pressure in the servo unit. On the basis of the measurements provided by this sensor, the ECU drives the motor so as to maintain accumulator pressure within a specified range.

4.3. Pedal Stroke Sensor

A pedal stroke sensor is used to detect the amount of brake pedal operation by the driver, since the pressure sensors alone are unable to detect a failure in the event of a mechanical breakdown in the servo unit.

The pedal stroke sensor is a rotary sliding resistance-type sensor. It is mounted to the brake pedal bracket, and converts the pedal stroke to rotary motion by means of a link.

5. Performance and Reliability of Service Brakes

The performance and brake feel of the service brakes are dependent on the characteristics of the hydraulic servo. To achieve high reliability, it is necessary to use a design that considers performance during system malfunctions. This section will discuss the element technologies used to enhance the performance and reliability of the service brakes (one of the development goals) and the achieved level of performance.

5.1. Configuration of Hydraulic Servo

The hydraulic servo is composed of a stroke simulator, which generates a stroke in response to pedal input and transmits the input force to the regulator valve, and the regulator valve itself, which is a mechanical servo valve that adjusts the pressure supplied by the power unit proportionally to the pedal input.

The pressure adjusted by the regulator valve (the regulator pressure) is applied to the back wall of the master cylinder (the power chamber), which operates the master cylinder piston, generating brake line pressure.

5.2. Stroke Simulator

As shown in Fig. 5, a rubber element (stroke damper) and a spring are positioned in line inside the stroke simulator. Pedal input causes the spring elements to be compressed in sequence, generating a pedal stroke. The relationship between pedal force and pedal stroke is determined by the characteristics of these spring elements and is not affected by the brake line pressure. Pedal feel therefore remains constant, regardless of the control being applied to the brake line pressure.

The internal spring is used to ensure a loss stroke in initial input, therefore the displacement of this spring is small. The pedal stroke is determined by the amount of compression of the stroke damper; the characteristics of the rubber used are therefore important elements in the brake feel achieved.

The hardness and the level of hysteresis of the rubber, which determine its basic characteristics, were adjusted to achieve excellent brake feel. To ensure stable brake feel, a rubber material was selected that displays little change in hardness with changes in temperature.

In standard brake systems, the relationship between pedal force and pedal stroke is nonlinear; the amount of change of the stroke becomes lower as the pedal force increases. Because the spring characteristic of the rubber is basically linear, this causes brake feel to decline. The cylinder (control piston) into which the stroke damper is inserted is therefore tapered. When the stroke increases,

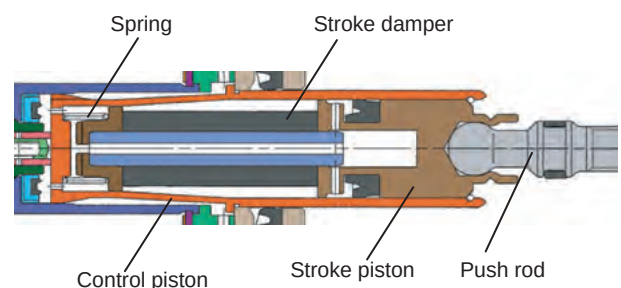


Fig. 5 Cross-section of stroke simulator

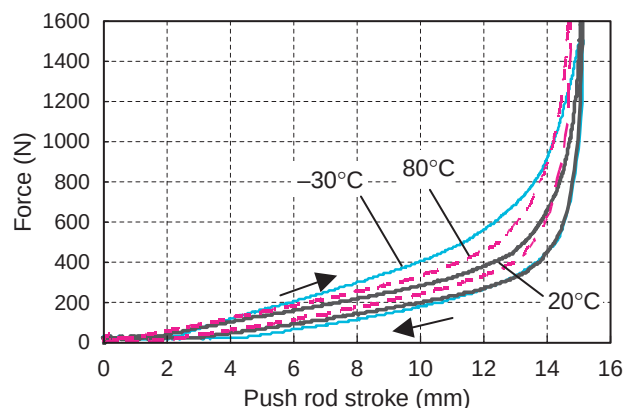


Fig. 6 Characteristic of stroke simulator

the end of the stroke damper fills the cylinder progressively, providing a nonlinear spring characteristic.

Figure 6 shows the characteristic of the stroke simulator at a range of temperatures. These results demonstrate that the relationship between stroke and input force has a low level of temperature dependence and that the tapered shape has resulted in the achievement of a nonlinear characteristic.

5.3. Regulator Valve

The regulator valve, shown in Fig. 7, is composed of an inlet valve that introduces the pressure from the accumulator into the regulator chamber when force is applied to the brake pedal and an outlet valve that releases pressure from the regulator chamber when the brake pedal force is reduced. When the brakes are not in operation, the inlet valve is sealed to maintain the pressure in the accumulator while the outlet valve remains open to release pressure from the regulator. When the brakes are operated, the input force on the pedal is transmitted to a reaction piston by the stroke simulator. The reaction piston moves forward, closing the outlet valve and opening the inlet valve. The pressure introduced through the inlet valve produces reaction force to the reaction piston; when the reaction piston reaches a position at which the pedal input force and the reaction force are in equilibrium, the inlet and outlet valves are closed, determining the regulator pressure. When the brakes are released, the reaction piston moves back until the outlet valve opens, and the regulator pressure is relieved.

Because an input force is required to oppose the accumulator pressure when the inlet valve is open, if the diameter of the inlet valve seal is too large, the threshold force at which brake line pressure begins to be produced is also high, and the brakes can appear not to be functioning. On the other hand, if the seal is small, the channel that introduces accumulator pressure is restricted, and pressure rises relatively slowly during panic stop compared to the normal brake system. A two-step seal system was used to address this issue. During the initial input, the low-diameter seal opens under a low load, resulting in a reduced threshold force. When the input is quick and there is a delay in the response of the regulator pressure, the shaft stroke increases to open the large-diameter seal, ensuring high output pressure response.

Figure 8 shows the relationship between pedal force and output pressure and Fig. 9 compares the pressure rise response at quick pedal input in the newly developed and previous systems. The two-step seal system ensures that the pedal force at which output pressure begins to be generated is the same as it was for the vacuum servo system. In addition, it enables an enhanced pressure rise response compared to that of the vacuum servo system.

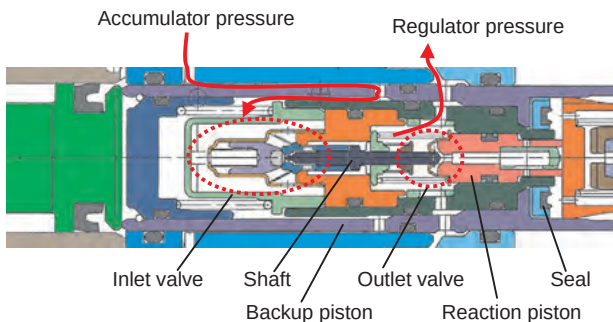


Fig. 7 Cross-section of regulator valve

5.4. Performance during Power Unit Malfunction

The hydraulic servo ceases to function when accumulator pressure is lost due to a malfunction. In the event of a malfunction, the pedal input is therefore transmitted directly to the master cylinder via the stroke simulator and a backup piston. This force is used to operate the master cylinder with no servo, enabling the brakes to function as effectively as the brakes in a vacuum servo system during a malfunction.

Under these circumstances, when the stroke simulator generates a stroke, the pedal stroke is longer than that produced by a vacuum servo. To control the stroke generated by the stroke simulator, a seal is positioned on the backup piston where it makes contact with the simulator. This seal blocks the channel for escape of brake fluid from the interior of the stroke simulator. The interior of the simulator fills with brake fluid, resulting in a restricted stroke.

Figure 10 shows the pedal stroke characteristic during a malfunction of the power unit. Restriction of the simulator stroke has ensured that the pedal stroke maintains the same level as the stroke in a vacuum servo system.

5.5. Reliability of Electrical System and Configuration of ECU

Because loss of power unit function would mean a decline in braking performance in a hydraulic servo system, the reliability of the drive circuits of the power unit motor was an important issue in the design of the ECU. In the newly developed system, the power

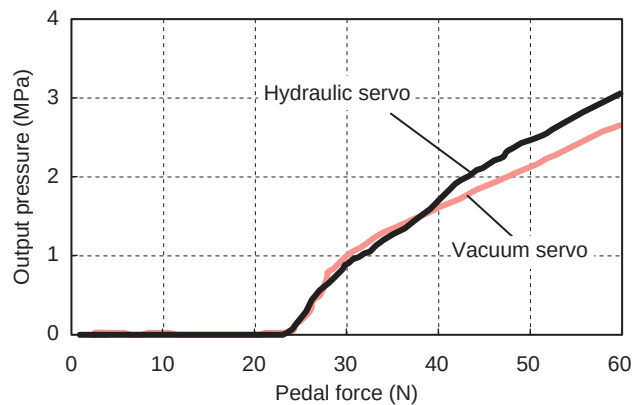


Fig. 8 Input and output characteristics

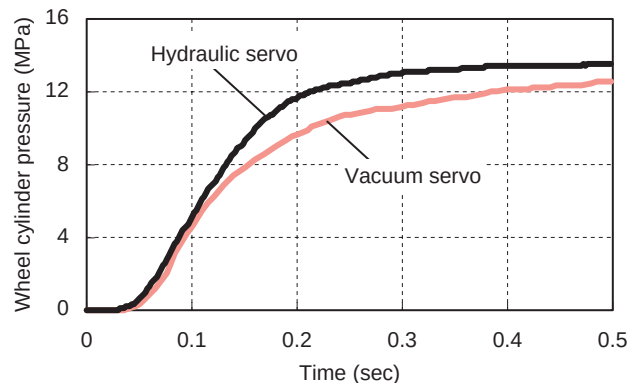


Fig. 9 Wheel cylinder pressure response at quick pedal input

source, CPU and power elements of the motor drive circuits are all made redundant. Motor function is therefore maintained in the event of a single failure, ensuring a high level of reliability.

In addition, the pressure sensor that monitors accumulator pressure is a two-output type, increasing the ability to detect a malfunction.

A fail-safe FET has been used in the power supply line for the solenoid valves to enable the power supply to be stopped in the event of a malfunction. The service brakes can be operated mechanically, and therefore brake performance is not lost even if the solenoid valve stops functioning. Figure 11 shows the configuration of the ECU hardware.

6. Control of Brake Line Pressure

To control brake pressure, a target value for pressure in the power chamber is determined on the basis of the requirements of each of the control functions; the solenoid valves are operated to produce the target brake pressure based on feedback from the fluid pressure sensors in the power chamber.

As indicated above, the use of a stroke simulator has ensured that the relationship between pedal force and stroke is not affected by control of brake pressure. Therefore, excellent brake feel can be achieved if brake pressure control is able to accurately trace the target pressure. Sliding mode control, known to possess excellent robustness⁽⁸⁾, is used in the newly developed system to ensure accurate brake pressure control.

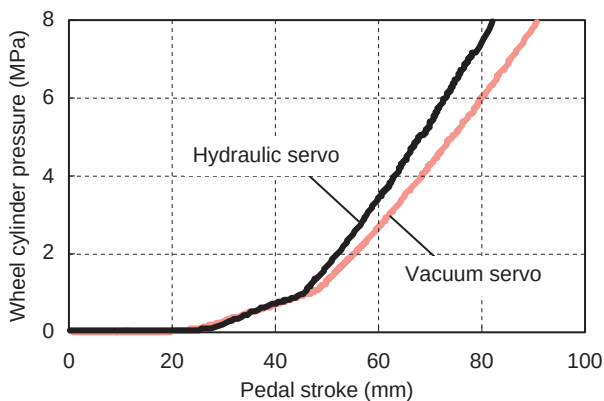


Fig. 10 Pedal stroke characteristics at power unit malfunction

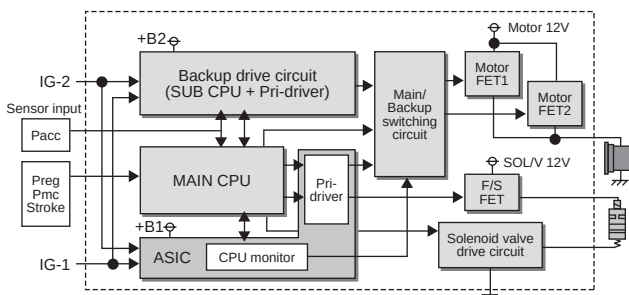


Fig. 11 ECU hardware block diagram

6.1. Solenoid Valve

Cooperative control of regenerative and hydraulic braking requires the application of control to reduce the pressure in the power chamber against the pressure in the regulator, which represents the force required for the operation of the brakes by the driver. On the other hand, control must sometimes be applied to increase pressure in order to generate brake line pressure without relation to the brake pedal operation or in excess of the brake pedal operation. To enable these different pressure control requirements to be realized, two solenoid valves for pressure decrease and two solenoid valves for pressure increase have been positioned between the regulator chamber and the power chamber in the servo unit. Pressure increases and pressure decreases control both function by isolating the power chamber from the regulator valve output and controlling the pressure in the power chamber.

Control is applied to two solenoid valves when using cooperative control of the regenerative and hydraulic brakes: a normal closed valve (NC/V) for pressure decrease that releases pressure from the power chamber into the reservoir and a normal open valve (NO/V) for pressure decrease that isolates the power chamber from the regulator output to maintain its state of reduced pressure. When applying control to increase the brake pressure in excess of the brake pedal operation, control is applied to another two solenoid valves: an NC/V for pressure increase, which introduces pressure stored in the accumulator into the power chamber, and an NO/V for pressure increase that isolates the power chamber from the regulator output to maintain its state of increased pressure. Figure 12 shows the layout of these solenoid valves. All of these solenoid valves are able to be used for linear pressure control.

6.2. Sliding Mode Control

Figure 13 shows an outline of sliding mode control. The present difference between control target pressure and control pressure, $e(n)$, and the previous difference between these parameters, $e(n-1)$, are used as state variables. A function termed the switching line is defined on the phase plane between these variables used as coordinate axes as

$$\sigma(n) = e(n) + s \cdot e(n-1) = 0 \quad (1)$$

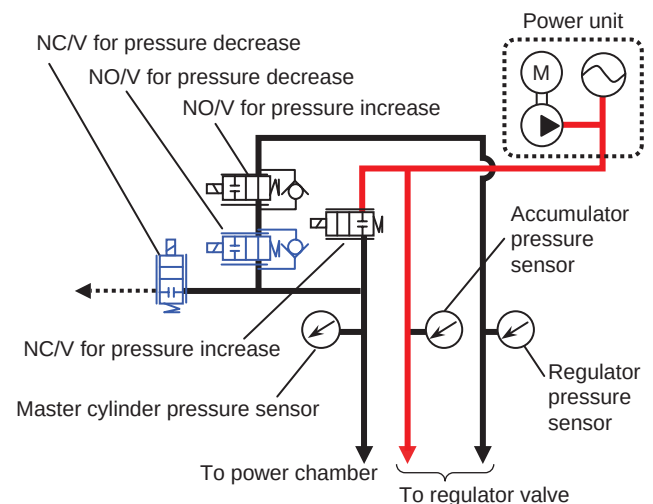


Fig. 12 Layout of solenoid valve

Control is applied to constrain the status level, representing the function of the state variables, to the switching line. If the gradient of the switching line, s , is set between 0 and -1 , the status level is constrained to the origin point of the phase plane, i.e. where the difference between target pressure and pressure = 0, and the control pressure matches target pressure.

The sum of three inputs is used as the control input to constrain the status level to the switching line; $U_{eq}(n)$, the equivalent control input enabling the status level to be constrained to the switching line; $U_{rch}(n)$, the reaching law input enabling the status level to be reached on the switching line; and $U_{adp}(n)$, the adaptive law input that controls modeling error and external disturbances to enable the status level to be maintained on the switching line⁽⁹⁾. These control inputs are determined as discussed below.

A discrete-time first-order lag model is used to define the pressure response of the solenoid valves that are subject to control.

$$P_{mc}(n+1) = a \cdot P_{mc}(n) + (1-a) \cdot U(n) \quad (2)$$

$P_{mc}(n)$: Control pressure

$U(n)$: Control input

a : Model parameter

Terming the control target pressure $P_{ref}(n)$, the difference $e(n)$ and the switching function $\sigma(n)$ are defined by the following equations:

$$e(n) = P_{ref}(n) - P_{mc}(n) \quad (3)$$

$$\sigma(n) = e(n) + s \cdot e(n-1) \quad (4)$$

Given that the condition for continued constraint of the status level to the switching line is

$$\sigma(n+1) = \sigma(n) \quad (5)$$

the equivalent control input $U_{eq}(n)$ can be determined by solving Equations (2) – (5) for $U(n)$.

$$U_{eq}(n) = \{P_{ref}(n+1) - a \cdot P_{mc}(n) - (1-s) \cdot e(n) - s \cdot e(n-1)\} / (1-a) \quad (6)$$

The reaching law input $U_{rch}(n)$ makes the status level reach the switching line, i.e. the input at which $\sigma(n) = 0$, and is a proportional element.

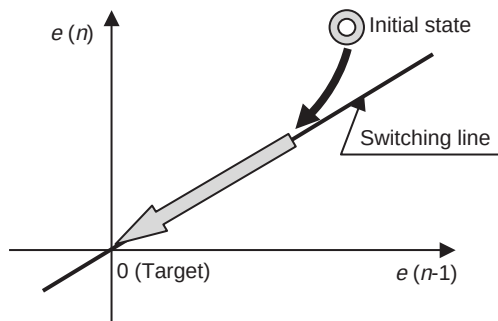


Fig. 13 Sliding mode control outline

$$U_{rch}(n) = F \cdot \sigma(n) \quad (7)$$

F : Feedback gain of reaching law

To reduce steady-state error, the adaptive law input $U_{adp}(n)$ is defined as an integral element of $\sigma(n)$ as follows:

$$U_{adp}(n) = G \cdot \sum_{i=0}^n \sigma(i) \quad (8)$$

G : Feedback gain of adaptive law

The control input $U_{in}(n)$ is the sum of the three inputs discussed above:

$$U_{in}(n) = U_{eq}(n) + U_{rch}(n) + U_{adp}(n) \quad (9)$$

6.3. Cooperative Control of Regenerative and Hydraulic Brakes

The distribution of braking force between regenerative and hydraulic brakes is determined so as to enable the regenerative brakes to be utilized as much as possible up to the limit of capacity for torque regeneration by the hybrid motor under a range of driving conditions. The control target for brake line pressure is determined by subtracting the pressure corresponding to regenerated torque from the figure provided by the fluid pressure sensor in the regulator chamber. The regulator pressure corresponds to the braking force required by the driver.

Brake line pressure control isolates the output from the regulator via the NO/V for pressure decrease, and decreases the pressure in the power chamber via the NC/V for pressure decrease. When the amount of regenerated torque decreases, pressure from the regulator is introduced to the power chamber via the NO/V for pressure decrease, thus increasing power chamber pressure. If this power chamber pressure control does not have sufficient ability to achieve the target pressure, the braking force required by the driver will not be produced.

Sliding mode control is applied to the NC/V when the pressure in the power chamber is reduced and to the NO/V when the pressure in the power chamber is increased. Fine-tuning of the control parameters for each solenoid valve has resulted in the achievement of highly responsive and stable pressure control, even under conditions such as temperature changes, which could cause modeling errors. The application of sliding mode control has ensured comfortable brake feel under a variety of driving conditions.

Figure 14 shows braking pressure during cooperative control of regenerative and hydraulic brakes. The control target pressure, representing pressure corresponding to regenerated torque

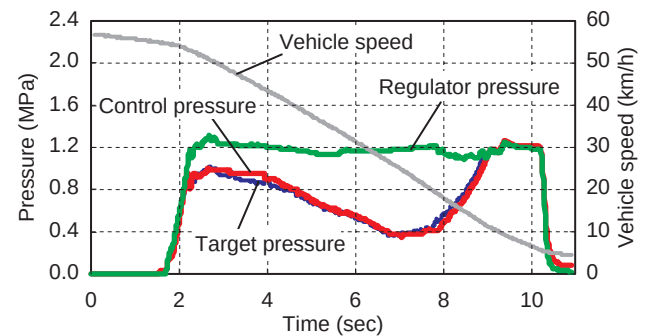


Fig. 14 Braking pressure during cooperative control

subtracted from regulator pressure, increases and decreases to match changes in the amount of torque that is able to be regenerated. The power chamber pressure, i.e. the control pressure, is able to trace this target pressure accurately.

6.4. Linear Control of Pressure Increase

Linear control of pressure increase via the two solenoid valves discussed above (the NC/V for pressure increase and the NO/V for pressure increase) has been enabled to respond to the requirement to generate braking line pressure in excess of the braking pressure represented by driver pedal input. When increased pressure is required, the NO/V for pressure increase isolates the output from the regulator, and the NC/V for pressure increase introduces pressure from the accumulator into the power chamber. To reduce the pressure in the power chamber, the NO/V for pressure increase is opened, and pressure is released into the regulator chamber.

As is the case for cooperative control of the brakes, sliding mode control is used for pressure control, ensuring excellent control performance.

7. Improved Fuel Economy

Fitted in a hybrid vehicle, the new system results in increased fuel economy in US LA-4 city mode. In the previous system, which was not provided with cooperative control, it was necessary to limit torque regeneration to maintain brake feel, and the ability of the hybrid motor to regenerate torque could not be utilized to its full capacity. The use of the newly developed system has enabled more efficient capture of regenerative energy, and the test vehicle regenerated approximately 46% more energy than the previous system during the test. Using this energy to drive the motor reduces the workload on the engine, resulting in a contribution to increased fuel economy.

8. Conclusion

A highly reliable hydraulic servo system able to ensure excellent brake feel has been used as a base in the development of a brake system that realizes a variety of brake control functions, including cooperative control of regenerative and hydraulic brakes. The main element technologies are as follows:

- (1) Fine-tuning of the characteristics of the stroke simulator and the use of a two-step inlet valve in the regulator resulted in the achievement of excellent brake feel.
- (2) High reliability has been ensured by making the power unit motor drive circuits redundant and using two-output-type sensors.
- (3) Highly accurate brake line pressure control has been achieved by applying sliding mode control to feedback control using solenoid valves.
- (4) Cooperative control of regenerative and hydraulic brakes has increased energy regeneration by 46%, resulting in a contribution to increased fuel economy.

The system discussed in this paper was developed to respond to the requirements of hybrid vehicles, but the control of brake line pressure as demanded that has been achieved can also respond to requirements for a variety of other braking functions, which will increase in the future. The potential of this system is not limited to hybrid vehicles; it can also contribute to enhanced brake performance and an increased range of brake function in other vehicle types.

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