

Development of an Electrically Driven Intelligent Brake System

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ABSTRACT

This paper presents an electrically driven intelligent brake system that has been developed for electric vehicles and hybrid electric vehicles, which are expected to penetrate markets rapidly amid the ongoing energy paradigm shift. This brake system achieves a cooperative energy regeneration function and high responsiveness while providing braking performance, system reliability and vehicle mounting ease equal to that of conventional brake systems with a vacuum booster. This paper outlines the newly developed brake system and describes various issues involved in cooperative regenerative braking along with the technologies that were applied to address them.

INTRODUCTION

In December 2006, Nissan announced a medium-term environmental action plan called the Nissan Green Program 2010. In addition to continuing to improve the efficiency and fuel economy of gasoline-fueled engines, we are also developing hybrid and plug-in hybrid cars, fuel-cell vehicles and electric cars as part of our medium- to long-term vision.

This paper describes an electrically driven intelligent brake system that has been developed under this program and incorporates a cooperative regenerative braking function. This brake system is used on the Leaf electric vehicle (EV) released in 2010 and the Infiniti M Hybrid to be released in 2011.

One effective method of improving the energy consumption rate of EVs and hybrid electric vehicles (HEVs) is

cooperative regenerative braking, whereby energy consumed during vehicle acceleration is recovered during deceleration as kinetic energy that is used to drive a motor for generating electricity again. However, conventional cooperative regenerative braking systems have not been able to fully recover kinetic energy during deceleration owing to the difficulty of reconciling energy regeneration with braking performance and vehicle behavior.

The brake system described here embodies the following features to achieve a cooperative regenerative braking capability for efficient energy recovery without sacrificing braking performance or vehicle stability.

- It incorporates a mechanism for directly converting the rotational motion of an electric motor integrated into the brake unit for use as the booster source instead of using the engine manifold vacuum as conventional brake systems do. This results in a highly responsive on-demand system.
- It reconciles cooperative energy regeneration with braking performance matching the vehicle characteristics by the brake unit built without stroke simulator.

This brake system is designed for EV and HEV applications where it is not possible to use the conventional engine manifold vacuum. The system merely replaces the traditional vacuum booster with an internal stroke simulator for generating the brake pedal reaction force perceived by the driver. As such, this system does not require the addition of any new components such as an accumulator or a vacuum pump, which have been needed in conventional regenerative braking systems. This means that there is no worry about the assurance of reliability, which can become a concern when a system increases in complexity due to the addition of

components, nor are there any layout concerns due to an increased part count. These are still other noteworthy advantages of this brake system.

This paper describes the electrically driven intelligent brake system that facilitates cooperative regenerative braking for extending the driving range or improving fuel economy and explains the method devised to control the system. It also presents the results obtained when the system was applied to a rear-wheel-drive HEV.

DEVELOPMENT AIMS

First, the importance of cooperative regenerative braking is described along with the development aims set for this brake system.

IMPORTANCE OF COOPERATIVE REGENERATIVE BRAKING

The question of how to suppress energy consumption is a critical issue in trying to improve the driving range of EVs or the fuel economy of HEVs. The following approaches can be cited as being effective in this regard.

- Instead of dissipating a moving vehicle's kinetic energy in the form of heat energy during braking, it can be recovered and stored temporarily as electrical energy that is reused again as kinetic energy for propelling the vehicle.
- Energy can be regenerated not only during coasting but also in the region of braking by the driver.

As illustrated in Fig. 1, energy losses can be substantially reduced by reusing the kinetic energy normally dissipated as heat energy during deceleration in an internal combustion engine (ICE) vehicle. This energy regeneration technology is indispensable for improving fuel economy and extending the driving range.

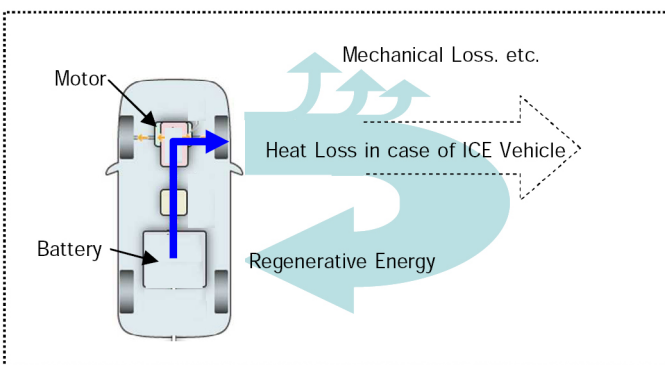


Fig. 1. Energy flow

The recently released EV and HEV mentioned earlier adopt a system in which the electric drive motor is used as a generator during vehicle deceleration to produce electrical

energy that is stored in the main battery by means of an inverter. The energy recovery rate is substantially improved by cooperative regenerative braking. The amount of energy that can be regenerated during coasting with the driver's foot off the accelerator is limited by driveability considerations. However, by regenerating energy even in the region of deceleration due to braking by the driver, the inherent potential of the motor, inverter and battery can be fully utilized. This makes it possible to improve the energy recovery rate markedly.

However, regenerative braking alone cannot provide sufficient brake force to decelerate a several-ton vehicle at a maximum deceleration rate of 1G. For that reason, it is necessary to use conventional hydraulic friction brakes in parallel with regenerative braking as shown in Fig. 2. The use of different actuators to achieve the braking performance demanded by the driver requires a system with exceptionally high accuracy and high responsiveness as well as sophisticated control technology.

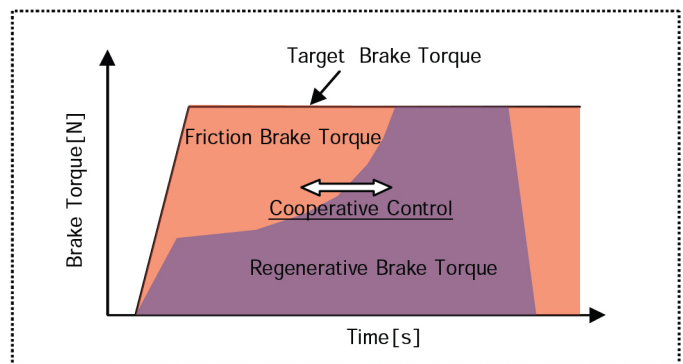


Fig. 2. Target characteristics

The following development aims were set for the electrically driven intelligent brake system.

- To achieve an overwhelmingly wide energy regeneration region capable of covering more than 80% of the actual braking situations under the LA4 urban driving cycle.
- To achieve natural braking performance, which is not perceived as cooperative regenerative braking, through a highly precise blend of regenerative brake torque and friction brake torque.

One issue that had to be addressed to achieve these aims is the effect of regenerative braking on vehicle behavior, which is described below.

EFFECT OF COOPERATIVE REGENERATIVE BRAKING ON VEHICLE BEHAVIOR

The ideal brake force distribution curve is shown theoretically in Fig. 3. In actuality, vehicle behavior becomes

unstable if the rear wheels lock before the front wheels. To avoid that, more brake force is generally distributed to the front wheels while still approximating the ideal brake force distribution curve. In a conventional brake system that does not perform cooperative regenerative braking, the real brake force distribution is predetermined according to the vehicle's front-rear weight distribution and the specifications of the brake calipers, pads and rotors.

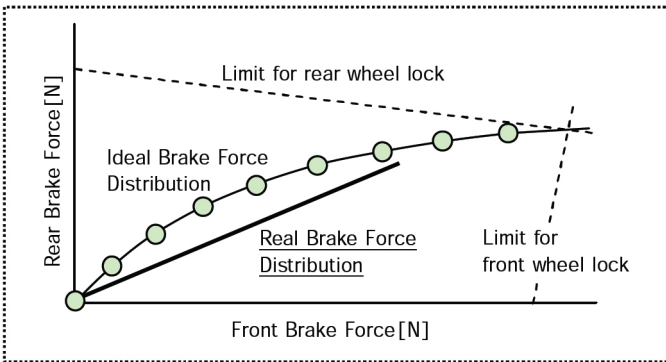


Fig. 3. Ideal brake force distribution

With cooperative regenerative braking, the originally determined brake force distribution is not obtained because brake force acts only on the drive wheels. Brake force has to be generated at the drive wheels alone while still maintaining the vehicle's total braking capability. As a result, the above-mentioned distribution between regenerative and friction brake forces cannot be maintained. As shown in Fig. 4, excess brake force is distributed to the front wheels in the case of a front-drive vehicle and to the rear wheels in the case of a rear-drive vehicle. The brake force and cornering force generated by the tires are closely related as seen in the concept of the friction circle. In rear-drive vehicles in particular, the cornering force produced by the rear wheels functions to stabilize vehicle behavior. Accordingly, if regenerative braking caused that cornering force to decline, it would produce an oversteer tendency, resulting in a deterioration of vehicle behavior. It is desirable to recover as much kinetic energy as possible for improving the driving range and fuel economy. However, with respect to vehicle behavior, the brake force distribution would increasingly deviate from the ideal curve as the amount of energy regenerated increases, and the cornering force would decrease accordingly. As a result, regenerative braking would have a pronounced impact on vehicle behavior when cornering on low- μ road surfaces where the friction circle becomes smaller.

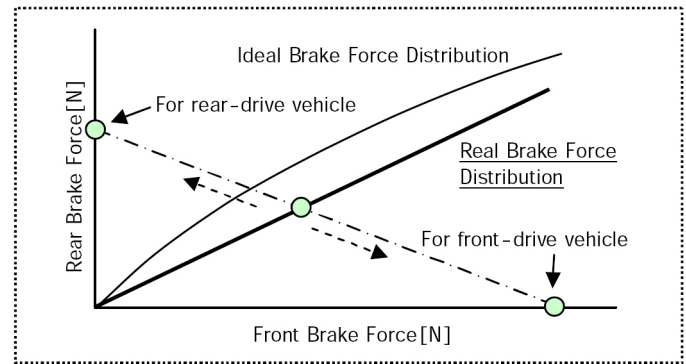


Fig. 4. Brake force distribution with regenerative braking

Because of this impact on vehicle behavior, it has so far not been possible to secure ample energy recovery by regenerative braking. The cooperative regenerative brake function described here has been developed to take vehicle behavior into account, making it possible to maximize energy regeneration for improving the driving range of EVs and the fuel economy of HEVs.

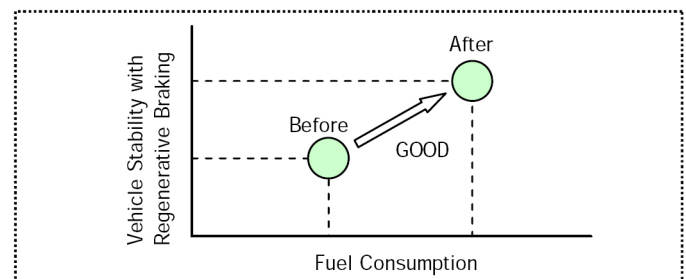


Fig. 5. Stability and fuel consumption targets

SYSTEM CONFIGURATION

The system configuration is shown schematically in Fig. 6. This brake system mainly consists of a stroke sensor for detecting the driver's brake pedal inputs, a master cylinder pressure sensor for detecting the brake fluid pressure generated by the brake master cylinder, and an electrically driven intelligent brake unit that controls the generation of fluid pressure by the brake master cylinder according to the driver's brake pedal inputs and cooperative regenerative braking. The electrically driven intelligent brake unit is located in the same position as a conventional vacuum booster. The components used downstream of this unit are a conventional vehicle dynamics control (VDC) system and foundation brake units. This intelligent brake system has been configured with the minimum number of changes relative to the brake system of conventional ICE vehicles.