

Development of a Slip Control System for RWD Hybrid Vehicles using Integrated Motor-Clutch Control

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ABSTRACT

The one-motor, two-clutch hybrid system adopted by Nissan requires high control performance for the entire system, because the single motor provides the various functions of a drive motor, generator and engine starter depending on the driving situation. An especially challenging problem is to prevent the motor torque variation caused by engine start while transmitting driving torque to the drive wheels in a situation where the engine is started in response to the driver's demand for acceleration during motor-only operation.

In this case, it is effective to let the clutch on the driving side slip until engine start is completed. For that purpose, we designed the slip control system described here. This system controls driving torque by the clutch while controlling the slip speed by means of the motor speed control. The slip speed can be controlled with high accuracy because the motor speed is controlled by the motor torque which is easily controllable. Furthermore, highly accurate driving torque is achieved without using a sensor. This is possible because the control system can use feedback control by estimating the driving torque from various information about the vehicle.

Bench and driving tests were conducted to evaluate the effectiveness of this control system. The experimental results showed that the slip speed and the driving torque tracked the respective target well. The results also showed that the control system achieved smooth vehicle acceleration with little vibration when the engine was started in response to the driver's demand for acceleration during motor-only operation.

1. 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 internal-combustion 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. Based on this plan, an original rear-wheel-drive (RWD) hybrid vehicle was released in North America and Japan in the autumn of 2010. Through the combined operation of the engine and electric drive motor, this hybrid vehicle achieves improved environmental performance and also better response to the driver's demand for acceleration than conventional vehicles.

Figure 1 shows the powertrain of this Nissan original hybrid vehicle [1]. The engine, motor and drive wheels are directly connected by two electronically controlled clutches. This hybrid system was created by removing the torque converter from a conventional 7-speed automatic transmission [2] and inserting one clutch and one drive motor. The vehicle can be driven by either the motor or the engine alone or by both power sources together, and can also be decelerated by regenerative braking with the motor. These functions are made possible by controlling the two clutches appropriately in response to the state of the engine. One clutch (denoted as clutch-1) is located between the engine and the motor, and the other clutch (denoted as clutch-2) is located in the 7-speed automatic transmission between the motor and the drive wheels.

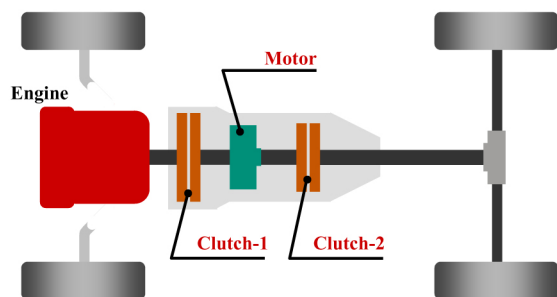


Figure 1. Powertrain of the Nissan Hybrid Vehicle

A major feature of this system is that the single motor both starts the engine and provides driving torque. The motor performs these two functions simultaneously in situations where the engine is started during motor drive. This gives rise to a difficulty in ensuring drivability because the motor torque variation caused by engine start is transmitted to the driving wheels together with the required motor torque. Therefore, it is necessary to prevent this motor torque variation while transmitting driving torque to the drive wheels.

To solve this problem, a new technique was developed for letting clutch-2 slip until the engine is started. This paper describes this technique, which is integrated in the control system for both the motor and clutch-2, and presents the results of vehicle experiments to demonstrate its effectiveness.

2. SYSTEM FEATURES

Figure 2 shows the structure of this hybrid system which is of the one-motor, two-clutch type.

Clutch-1 located between the engine and the motor is a dry clutch that fully prevents motor torque from being transmitted to the engine when the clutch is disengaged. This clutch has been diverted from a manual transmission, and a position sensor and a hydraulic pressure actuator have been added for controlling the position of the clutch disc by applying pressure to it. The torque capacity of clutch-1 is controlled by varying the position of the clutch disc.

Clutch-2 serves to shift the automatic transmission, and its torque capacity is controlled by modulating the hydraulic pressure. The characteristics from the pressure command value to the actual torque capacity are apt to change under the effects of temperature variation, aging, or variability in manufacturing. However, a hydraulic pressure sensor has not been applied for detecting the equivalent torque capacity value directly because the system selects a different clutch as clutch-2 depending on the transmission gear involved.

The motor is a three-phase alternating current synchronous motor which was newly developed. The motor torque is

controlled with high accuracy and high response by means of feedback control of the current. The motor speed is also detected with high accuracy because a resolver is used as a rotary position sensor, and a feedback control system has been designed for the motor speed as well.

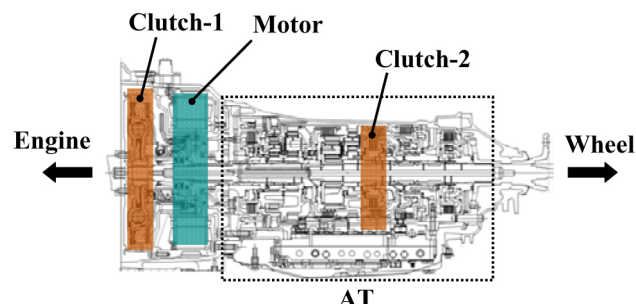


Figure 2. 1-Motor, 2-Clutch Hybrid System

Figure 3 shows the architecture of the controller in this hybrid system.

The hybrid controller comprehensively considers vehicle drivability and the efficiency of each unit, based on various information received about the vehicle and calculates the command values sent to the engine controller, the motor controller and the automatic transmission (AT) controller. Upon receiving a command from the hybrid controller, each controller acts to control its assigned part. The requisite information, including the command values and state quantities, is transmitted and received through a Controller Area Network (CAN).

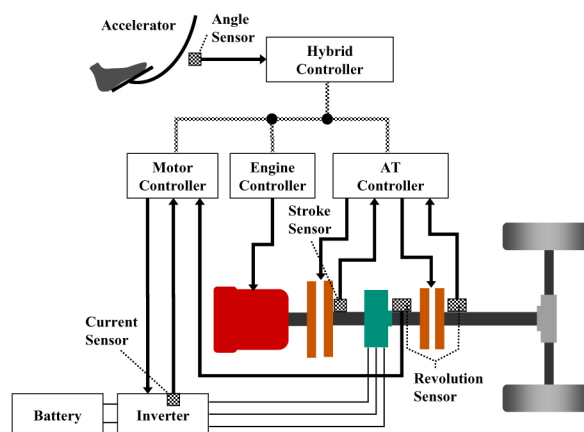


Figure 3. Architecture of the Control System

3. BASIC CONTROL STRATEGY FOR ENGINE START

Because the single motor in this hybrid system both starts the engine and provides driving torque, it was necessary to devise a control algorithm so that the motor torque variation caused

by engine start would not affect driving performance. In a situation where the engine is started during motor drive, if the clutch-1 torque capacity is increased little by little to prevent motor torque variation, the time needed to start the engine will be very long. Alternatively, if clutch-2 is completely disengaged so that motor torque variation is not transmitted to the drive wheels, it will be difficult to accelerate the vehicle. Therefore, clutch-2 is allowed to slip until the engine is started so that the torque variation is cut off and only torque equivalent to the torque capacity is transmitted to the drive wheels. To start the engine more quickly, it is necessary to shorten the time for letting clutch-2 slip. In this case, it is effective to let clutch-2 slip beforehand in motor drive prior to starting the engine. However, under a condition where large slip speed lasts a long time, additional problems arise such as the durability of clutch-2.

The following control algorithm was devised to deal with the situations described above. Clutch-2 is allowed to slip at a very small speed during motor drive. Therefore, clutch-2 slip doesn't influence the durability and the fuel economy. And the slip speed is increased to avoid transmitting motor torque variation to the drive wheels during engine start.

Clutch-2 is completely connected during hybrid drive after the engine is started. Figure 4 shows this mode transition. The following section describes the integrated control system of both the motor and clutch-2 that enables ideal engine start with this one-motor, two-clutch type of hybrid system.

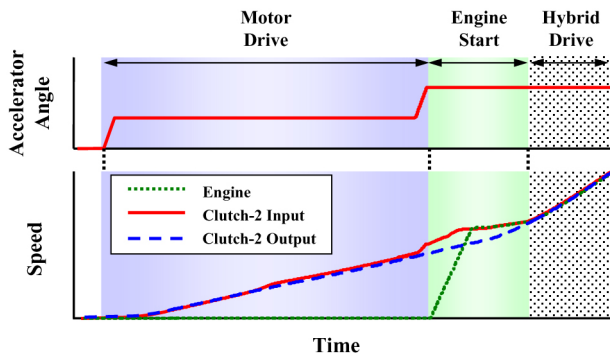


Figure 4. Concept of Engine Start Sequence

4. INTEGRATED CONTROL SYSTEM

The requirements for the engine start sequence shown in Figure 4 are described below.

1. To control the driving torque in response to the driver's demands
2. To control the slip speed according to the drive mode
3. To control the driving torque and the slip speed independently

Figure 5 shows the integrated control system that was designed to satisfy these requirements. The important points considered in designing this control system are described below.

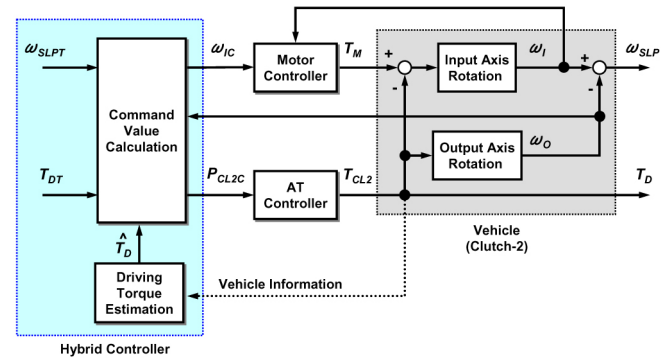


Figure 5. Integrated Control System

First, the strategy for meeting the first requirement is explained. The driving torque T_D of the vehicle while letting clutch-2 slip can be expressed as shown in Eq. (1) because the torque transmitted to the drive wheels depends on only the clutch-2 torque capacity T_{CL2} .

$$T_D = T_{CL2} \quad (1)$$

Therefore, the driving torque can be controlled by modulating the clutch-2 hydraulic pressure in relation to its torque capacity under a condition where the slipping of the clutch is maintained. The target driving torque is determined in response to the driver's accelerator input, and the clutch-2 pressure command value P_{CL2C} transmitted to the AT controller is calculated based on the target driving torque T_{DT} in the feedback control system. This feedback system is configured with the target driving torque and the estimated driving torque $\hat{T}_D$ which is calculated from various information about the vehicle. The hydraulic pressure of clutch-2 is controlled by the AT controller according to the command value. This feedback control system using the estimated driving torque makes it possible to control the actual driving torque with high accuracy even if the characteristic of clutch-2 changes significantly.

Next, the strategy for meeting the second requirement is explained. By letting clutch-2 slip, the input side and the output side are not a rigid body. In this case, the motion equation of the input side and that of the output side are expressed as shown below.

$$J_I \cdot \dot{\omega}_I + C_I \cdot \omega_I = T_M - T_{CL2} \quad (2)$$