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# Improvement of Shift Quality for Automatic Transmission based 2-shaft Parallel Hybrid Electric Vehicle by Motor Control

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**Abstract**

Improvement of shift quality is investigated for an automatic transmission based 2-shaft parallel hybrid electric vehicle(HEV) during the gear shift. First, dynamic models of HEV powertrain are obtained including the engine, motor, engine clutch and transmission. To obtain the improved shift quality, a motor torque control algorithm is proposed to reduce the driveshaft torque variation in the torque and inertia phase. The motor torque control algorithm is evaluated by the simulation and experiment. It is found that the motor torque control algorithm is able to reduce the torque variation effectively during the transient shift period for the automatic transmission based parallel HEV.

*Keywords: Hybrid Electric Vehicle, Automatic transmission, Shift Quality.*

## 1 Introduction

As the HEV(hybrid electric vehicle) transmission, continuously variable transmission, dual clutch transmission have been adapted for passenger cars. Toyota 'Prius' THS(Toyota hybrid system) is a power split type transmission which consists of planetary gear and two motors. Even if THS type power split transmission has many advantages such as no clutch, no starting device or simple structure[1], it also has demerits such as decreased transmission efficiency in high vehicle speed, relatively complicated control, which results from the two motor operation. Amongst all, the electrical power path which requires relatively large size two motors may be the biggest disadvantage because cost of the two motors and relating power electronics can not be easily lowered[2]. In order for the HEV to compete with the existing conventional vehicles, the extra cost for the hybridization should be minimized and acceptable for customers. From the viewpoint of the cost, it is required that hybrid vehicle transmission needs to be developed using the existing transmission technology and production lines.

A 2-shaft parallel HEV which adapts automatic transmission(AT) has some advantages[3] :

- can use the existing production facility
- relatively low cost since AT can be utilized from its mass production line

However, the following problems should be solved to compete with the power split type HEVs :

- torque shock during the shift
- the power loss of the hydraulic system to operate the clutch and brake actuator

In this paper, improvement of the shift quality for a AT based 2-shaft parallel HEV is investigated using the motor torque control. A motor torque control algorithm is proposed to reduce the torque variation during the gear shift. The motor torque control algorithm to improve the shift quality is evaluated by the simulations and experiments. HEV modelling

## 2 HEV modeling

### 2.1 HEV structure

In Figure 1, a AT based 2-shaft parallel HEV structure is shown. The HEV consists of a 4-speed automatic transmission and 12kW motor. In order to minimize the packaging space and realize the HEV functions, the torque converter is eliminated and the engine clutch is installed between the internal combustion engine(ICE) and the motor. In electric vehicle(EV) mode, the motor propels the vehicle through the automatic transmission meanwhile the engine and the motor drive the vehicle with the engine clutch engaged in HEV mode.

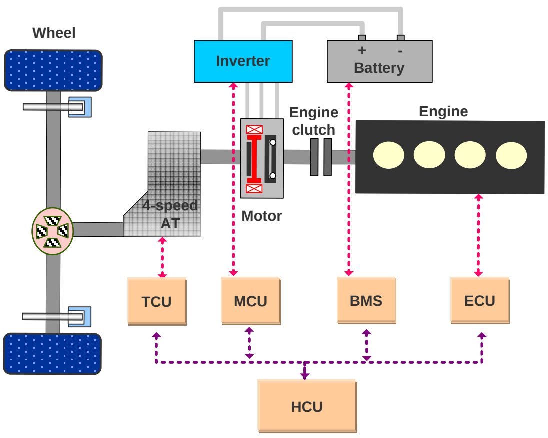


Figure : 1 AT based 2-shaft parallel HEV structure

### 2.2 HEV modeling

**Engine** : Figure 2 shows the engine characteristic map. The engine is modeled based on the characteristic map for the torque and speed with respect to the throttle opening

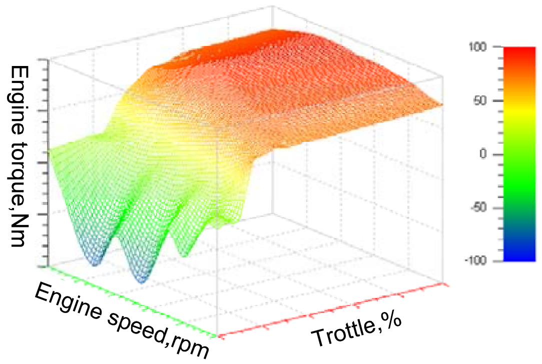


Figure 2 : Engine map

**Motor** : A 12 kW motor is used. In Figure 3, the motor efficiency map is shown. The motor is used as the generator during the regenerative braking.

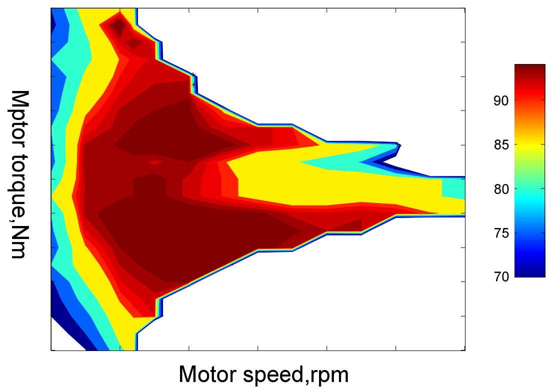


Figure 3 : Motor efficiency map

**Battery** : Battery is modeled based on the rated capacity, voltage, initial state of charge(SOC) and characteristic map. The battery output voltage and SOC can be calculated from the open circuit voltage and internal resistance characteristics.

**Engine clutch** : A wet type multi-disk type clutch is used for the mode change clutch. The torque and coefficient of friction of the wet type multi-disk clutch(Figure 4) are represented as :

$$T_{EC} = \mu NAP \frac{2(R_o^{\,3} - R_i^{\,3})}{3(R_o^{\,2} - R_i^{\,2})} \quad (4)$$

$$\mu = (\mu_s - \mu_k)\exp(-\Delta\omega/\omega_s) - \mu_k \quad (5)$$

where $N$ is the number of the clutch disc, $A$ is the actuator area, $P$ is the clutch pressure, $R_o$ is the outer radius of the clutch disc, $R_i$ is the inner radius of the clutch disc, $\mu_s$ is the static friction coefficient, $\mu_k$ is the dynamic friction coefficient, $\Delta\omega$ is the relative slip speed, $\omega_s$ is the steady state speed.

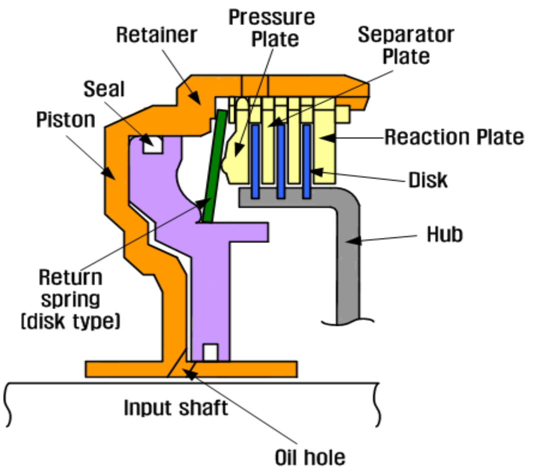


Figure 4 : Wet type multi-disk clutch

**Transmission** : Figure 5 shows the 4-speed AT used in the HEV. The AT in Figure 5 consists of 2 single pinion planetary gears, 2 clutches, and 2 brakes..

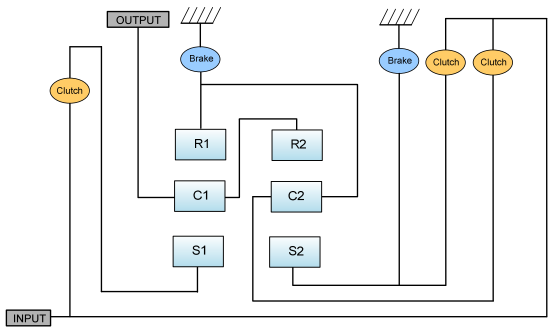


Figure 5 : 4-speed automatic transmission

## 2.3 HEV performance simulator

Using the HEV subsystem models, a HEV performance simulator is developed based on MATLAB Simulink and SimDriveline(Figure 6).

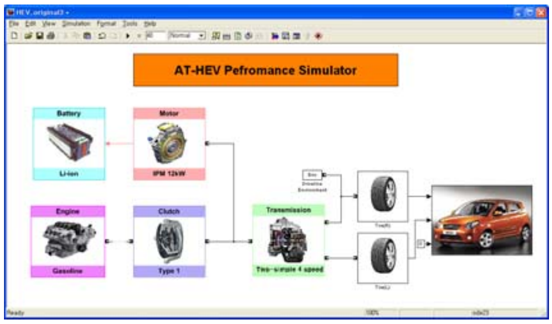


Figure 6 : HEV performance simulator

# 3 Motor Torque control for shift quality improvement

## 3.1 Motor torque control algorithm

In order to improve the shift quality during the gear shift, a motor torque control is introduced. Figure 7(a) shows the driveshaft torque response for a typical AT during the up-shift. The drive shaft torque decreases to the lowest value at the end of the torque phase and shows the highest value at the beginning stage of the inertia phase. Since the shift quality depends on the peak to peak change of the driveshaft torque, if we reduce the peak to peal torque by the motor torque control, improvement of the shift quality can be obtained. The motor torque control is proposed follows :

① Type1: motor torque control in inertia phase

② Type2: motor torque control in both torque and inertia phase

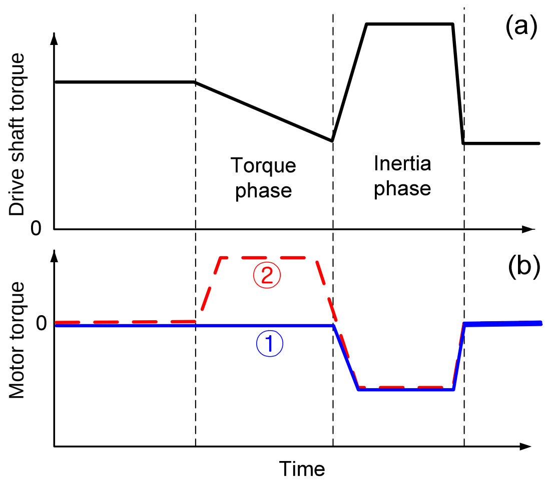


Figure 7 : Up-shift with motor torque control

The motor torque control strategy for the Type 1 and Type 2 is shown in Figure 7(b). In Type 1 control, the negative motor torque is applied in the inertia phase to reduce the positive overshoot torque. In Type 2 control, the positive torque is added to compensate the decreasing torque in the torque phase in addition to the negative torque compensation in the inertia phase.

### 3.2 Simulation results for shift quality improvement

In Figure 8, simulation results of the motor torque control are shown for 2-3 up-shift. For Type 1 control, the engine speed(b) decreases earlier than that of No control since the negative motor torque is applied in the inertia phase. It is seen that the peak torque of the inertia phase is reduced by the motor torque compensation. For the type 2 control, the engine speed(b) increases in the torque phase by the positive motor torque and decreases in the inertia phase by the negative motor torque. This motor torque compensation provides the reduced torque variation during the transient state of the shift. It is found that the peak to peak torque is reduced by 34.5% from 420Nm(No control) to 275Nm(Type 2 control)

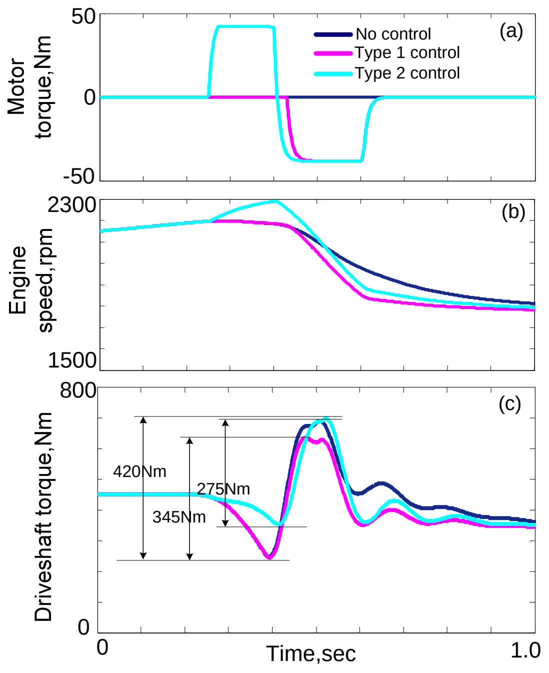


Figure 8 : Simulation results for motor torque control

## 4 Experiments

### 4.1 HEV bench tester

To evaluate the performance of the motor torque control algorithm experimentally, a HEV bench tester is designed and realized for the target hybrid electric vehicle. Figure 9 shows the bench tester designed in this study. The bench tester consists of the engine, clutch, motor, battery, automatic transmission, inertia and control system modules.

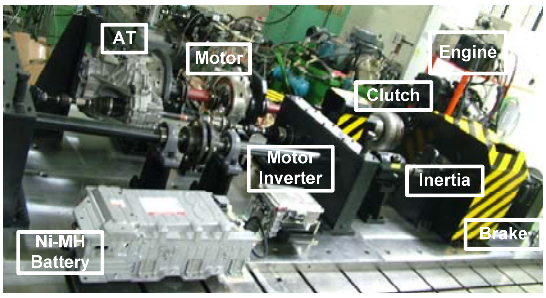


Figure 9 : HEV bench tester

The engine throttle is controlled by the servo motor. The engine clutch engagement is performed by the hydraulic pressure supplied by the separate power-pack. The engine clutch engagement is controlled by adjusting the clutch pressure profile. The motor, 4 speed automatic transmission and battery are controlled through CAN from the sensor signals of the torque, speed, voltage, current, speed ratio and temperature. The speed and torque of the engine and driveshaft are measured by the rotary encoder and torque sensor, respectively.

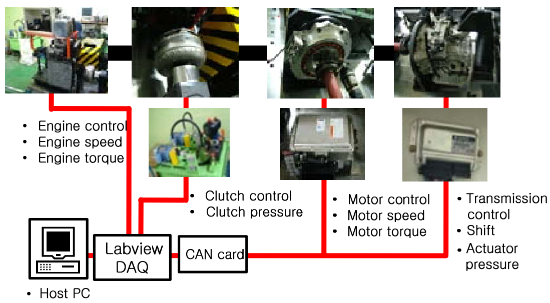


Figure 10 : Control for HEV bench tester

### 4.2 Experimental results and discussion

In Figure 11, the experimental results of the motor torque control are shown for 2-3 up-shift. The engine speed(b) shows similar response with the simulation results. The type 1 control reduces the peak torque in the inertia phase by the negative torque compensation. For the type 2 control, it is noted that the torque undershoot in the torque phase and the peak torque in the inertia phase are reduced by the motor torque control. The peak to peak torque can be reduced by 26.8% form 450Nm(No control) to 329Nm(Type 2 control)

It is noted that the driveshaft torque of the experiment shows more vibration than the simulation results. This vibration is considered to be induced by the bench tester configuration where the left and right side drive shafts are connected together.

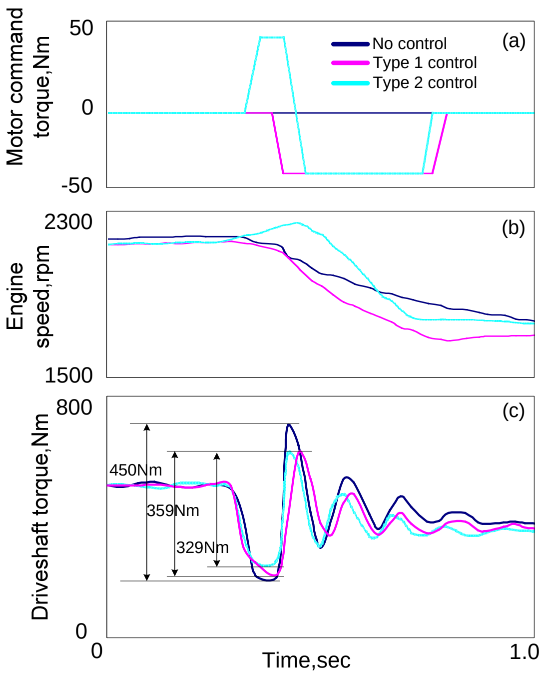


Figure 11 : Experimental results for 2-3 up-shift

## 5 Conclusion

Improvement of shift quality is investigated for an automatic transmission based 2-shaft parallel hybrid electric vehicle(HEV) during the gear shift. Dynamic models of the HEV powertrain are obtained including the engine, motor, engine clutch and transmission. To obtain the improved shift quality, a motor torque control algorithm is proposed to reduce the driveshaft torque variation in the torque and inertia phase. The motor torque control algorithm is evaluated by the simulation and experiment. It is found from the simulation and experimental results that the motor torque control algorithm is able to reduce the torque variation by 26.8% for the automatic transmission based parallel HEV.

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